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# Inclusive jet cross sections and dijet correlations in $D^{*\pm}$ photoproduction at HERA

ZEUS Collaboration

## Abstract

Inclusive jet cross sections in photoproduction for events containing a  $D^*$  meson have been measured with the ZEUS detector at HERA using an integrated luminosity of  $78.6 \text{ pb}^{-1}$ . The events were required to have a virtuality of the incoming photon,  $Q^2$ , of less than  $1 \text{ GeV}^2$ , and a photon-proton centre-of-mass energy in the range  $130 < W_{\gamma p} < 280 \text{ GeV}$ . The measurements are compared with next-to-leading-order (NLO) QCD calculations. Good agreement is found with the NLO calculations over most of the measured kinematic region. Requiring a second jet in the event allowed a more detailed comparison with QCD calculations. The measured dijet cross sections are also compared to Monte Carlo (MC) models which incorporate leading-order matrix elements followed by parton showers and hadronisation. The NLO QCD predictions are in general agreement with the data although differences have been isolated to regions where contributions from higher orders are expected to be significant. The MC models give a better description than the NLO predictions of the shape of the measured cross sections.

# The ZEUS Collaboration

S. Chekanov, M. Derrick, S. Magill, S. Miglioranzi<sup>1</sup>, B. Musgrave, J. Repond, R. Yoshida  
*Argonne National Laboratory, Argonne, Illinois 60439-4815, USA* <sup>n</sup>

M.C.K. Mattingly

*Andrews University, Berrien Springs, Michigan 49104-0380, USA*

N. Pavel, A.G. Yagües Molina

*Institut für Physik der Humboldt-Universität zu Berlin, Berlin, Germany*

P. Antonioli, G. Bari, M. Basile, L. Bellagamba, D. Boscherini, A. Bruni, G. Bruni,  
G. Cara Romeo, L. Cifarelli, F. Cindolo, A. Contin, M. Corradi, S. De Pasquale, P. Giusti,  
G. Iacobucci, A. Margotti, A. Montanari, R. Nania, F. Palmonari, A. Pesci, A. Polini,  
L. Rinaldi, G. Sartorelli, A. Zichichi

*University and INFN Bologna, Bologna, Italy* <sup>e</sup>

G. Aghuzumtsyan, D. Bartsch, I. Brock, S. Goers, H. Hartmann, E. Hilger, P. Irrgang<sup>2</sup>,  
H.-P. Jakob, O.M. Kind, U. Meyer, E. Paul<sup>3</sup>, J. Rautenberg, R. Renner, M. Wang,  
M. Wlasenko

*Physikalisches Institut der Universität Bonn, Bonn, Germany* <sup>b</sup>

D.S. Bailey<sup>4</sup>, N.H. Brook, J.E. Cole, G.P. Heath, T. Namsoo, S. Robins

*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom* <sup>m</sup>

M. Capua, S. Fazio, A. Mastroberardino, M. Schioppa, G. Susinno, E. Tassi

*Calabria University, Physics Department and INFN, Cosenza, Italy* <sup>e</sup>

J.Y. Kim, K.J. Ma<sup>5</sup>

*Chonnam National University, Kwangju, South Korea* <sup>g</sup>

M. Helbich, Y. Ning, Z. Ren, W.B. Schmidke, F. Sciulli

*Nevis Laboratories, Columbia University, Irvington on Hudson, New York 10027* <sup>o</sup>

J. Chwastowski, A. Eskreys, J. Figiel, A. Galas, M. Gil, K. Olkiewicz, P. Stopa, D. Szuba,  
L. Zawiejski

*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences,  
Cracow, Poland* <sup>i</sup>

L. Adamczyk, T. Bold, I. Grabowska-Bold, D. Kisielewska, J. Lukasik, M. Przybycień,  
L. Suszycki, J. Szuba<sup>6</sup>

*Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology,  
Cracow, Poland* <sup>p</sup>

A. Kotański<sup>7</sup>, W. Słomiński

*Department of Physics, Jagellonian University, Cracow, Poland*

V. Adler, U. Behrens, I. Bloch, K. Borras, G. Drews, J. Fourletova, A. Geiser, D. Gladkov, P. Göttlicher<sup>8</sup>, O. Gutsche, T. Haas, W. Hain, C. Horn, B. Kahle, U. Kötz, H. Kowalski, G. Kramberger, H. Lim, B. Löhr, R. Mankel, I.-A. Melzer-Pellmann, C.N. Nguyen, D. Notz, A.E. Nuncio-Quiroz, A. Raval, R. Santamarta, U. Schneekloth, H. Stadie, U. Stösslein, G. Wolf, C. Youngman, W. Zeuner

*Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*

S. Schlenstedt

*Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany*

G. Barbagli, E. Gallo, C. Genta, P. G. Pelfer

*University and INFN, Florence, Italy* <sup>e</sup>

A. Bamberger, A. Benen, F. Karstens, D. Dobur, N.N. Vlasov<sup>9</sup>

*Fakultät für Physik der Universität Freiburg i.Br., Freiburg i.Br., Germany* <sup>b</sup>

P.J. Bussey, A.T. Doyle, W. Dunne, J. Ferrando, J.H. McKenzie, D.H. Saxon, I.O. Skillicorn

*Department of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom* <sup>m</sup>

I. Gialas<sup>10</sup>

*Department of Engineering in Management and Finance, Univ. of Aegean, Greece*

T. Carli<sup>11</sup>, T. Gosau, U. Holm, N. Krumnack<sup>12</sup>, E. Lohrmann, M. Milite, H. Salehi, P. Schleper, T. Schörner-Sadenius, S. Stonjek<sup>13</sup>, K. Wichmann, K. Wick, A. Ziegler, Ar. Ziegler

*Hamburg University, Institute of Exp. Physics, Hamburg, Germany* <sup>b</sup>

C. Collins-Tooth<sup>14</sup>, C. Foudas, C. Fry, R. Gonçalo<sup>15</sup>, K.R. Long, A.D. Tapper

*Imperial College London, High Energy Nuclear Physics Group, London, United Kingdom* <sup>m</sup>

M. Kataoka<sup>16</sup>, K. Nagano, K. Tokushuku<sup>17</sup>, S. Yamada, Y. Yamazaki

*Institute of Particle and Nuclear Studies, KEK, Tsukuba, Japan* <sup>f</sup>

A.N. Barakbaev, E.G. Boos, N.S. Pokrovskiy, B.O. Zhautykov

*Institute of Physics and Technology of Ministry of Education and Science of Kazakhstan, Almaty, Kazakhstan*

D. Son

*Kyungpook National University, Center for High Energy Physics, Daegu, South Korea* <sup>g</sup>

J. de Favereau, K. Piotrzkowski

*Institut de Physique Nucléaire, Université Catholique de Louvain, Louvain-la-Neuve, Belgium* <sup>q</sup>

F. Barreiro, C. Glasman<sup>18</sup>, M. Jimenez, L. Labarga, J. del Peso, J. Terrón, M. Zambrana  
*Departamento de Física Teórica, Universidad Autónoma de Madrid, Madrid, Spain*<sup>l</sup>

F. Corriveau, C. Liu, M. Plamondon, A. Robichaud-Veronneau, R. Walsh, C. Zhou  
*Department of Physics, McGill University, Montréal, Québec, Canada H3A 2T8*<sup>a</sup>

T. Tsurugai  
*Meiji Gakuin University, Faculty of General Education, Yokohama, Japan*<sup>f</sup>

A. Antonov, B.A. Dolgoshein, I. Rubinsky, V. Sosnovtsev, A. Stifutkin, S. Suchkov  
*Moscow Engineering Physics Institute, Moscow, Russia*<sup>j</sup>

R.K. Dementiev, P.F. Ermolov, L.K. Gladilin, I.I. Katkov, L.A. Khein, I.A. Korzhavina, V.A. Kuzmin, B.B. Levchenko, O.Yu. Lukina, A.S. Proskuryakov, L.M. Shcheglova, D.S. Zotkin, S.A. Zotkin  
*Moscow State University, Institute of Nuclear Physics, Moscow, Russia*<sup>k</sup>

I. Abt, C. Büttner, A. Caldwell, X. Liu, J. Sutiak  
*Max-Planck-Institut für Physik, München, Germany*

N. Coppola, G. Grigorescu, A. Keramidas, E. Koffeman, P. Kooijman, E. Maddox, H. Tiecke, M. Vázquez, L. Wiggers  
*NIKHEF and University of Amsterdam, Amsterdam, Netherlands*<sup>h</sup>

N. Brümmer, B. Bylsma, L.S. Durkin, A. Lee, T.Y. Ling  
*Physics Department, Ohio State University, Columbus, Ohio 43210*<sup>n</sup>

P.D. Allfrey, M.A. Bell, A.M. Cooper-Sarkar, A. Cottrell, R.C.E. Devenish, B. Foster, C. Gwenlan<sup>19</sup>, T. Kohno, K. Korcsak-Gorzo, S. Patel, V. Roberfroid<sup>20</sup>, P.B. Straub, R. Walczak  
*Department of Physics, University of Oxford, Oxford United Kingdom*<sup>m</sup>

P. Bellan, A. Bertolin, R. Brugnera, R. Carlin, R. Ciesielski, F. Dal Corso, S. Dusini, A. Garfagnini, S. Limentani, A. Longhin, L. Stanco, M. Turcato  
*Dipartimento di Fisica dell' Università and INFN, Padova, Italy*<sup>e</sup>

E.A. Heaphy, F. Metlica, B.Y. Oh, J.J. Whitmore<sup>21</sup>  
*Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802*<sup>o</sup>

Y. Iga  
*Polytechnic University, Sagamihara, Japan*<sup>f</sup>

G. D'Agostini, G. Marini, A. Nigro  
*Dipartimento di Fisica, Università 'La Sapienza' and INFN, Rome, Italy*<sup>e</sup>

J.C. Hart

*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, United Kingdom<sup>m</sup>*

H. Abramowicz<sup>22</sup>, A. Gabareen, S. Kananov, A. Kreisel, A. Levy

*Raymond and Beverly Sackler Faculty of Exact Sciences, School of Physics, Tel-Aviv University, Tel-Aviv, Israel<sup>d</sup>*

M. Kuze

*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan<sup>f</sup>*

S. Kagawa, T. Tawara

*Department of Physics, University of Tokyo, Tokyo, Japan<sup>f</sup>*

R. Hamatsu, H. Kaji, S. Kitamura<sup>23</sup>, K. Matsuzawa, O. Ota, Y.D. Ri

*Tokyo Metropolitan University, Department of Physics, Tokyo, Japan<sup>f</sup>*

M. Costa, M.I. Ferrero, V. Monaco, R. Sacchi, A. Solano

*Università di Torino and INFN, Torino, Italy<sup>e</sup>*

M. Arneodo, M. Ruspa

*Università del Piemonte Orientale, Novara, and INFN, Torino, Italy<sup>e</sup>*

S. Fourletov, J.F. Martin

*Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7<sup>a</sup>*

J.M. Butterworth<sup>24</sup>, R. Hall-Wilton, T.W. Jones, J.H. Loizides<sup>25</sup>, M.R. Sutton<sup>4</sup>, C. Targett-Adams, M. Wing

*Physics and Astronomy Department, University College London, London, United Kingdom<sup>m</sup>*

J. Ciborowski<sup>26</sup>, G. Grzelak, P. Kulinski, P. Łužniak<sup>27</sup>, J. Malka<sup>27</sup>, R.J. Nowak, J.M. Pawlak, J. Sztuk<sup>28</sup>, T. Tymieniecka, A. Ukleja, J. Ukleja<sup>29</sup>, A.F. Żarnecki

*Warsaw University, Institute of Experimental Physics, Warsaw, Poland*

M. Adamus, P. Plucinski

*Institute for Nuclear Studies, Warsaw, Poland*

Y. Eisenberg, D. Hochman, U. Karshon, M.S. Lightwood

*Department of Particle Physics, Weizmann Institute, Rehovot, Israel<sup>c</sup>*

E. Brownson, T. Danielson, A. Everett, D. Kçira, S. Lammers, L. Li, D.D. Reeder, M. Rosin, P. Ryan, A.A. Savin, W.H. Smith

*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA<sup>n</sup>*

S. Dhawan

*Department of Physics, Yale University, New Haven, Connecticut 06520-8121, USA<sup>n</sup>*

S. Bhadra, C.D. Catterall, Y. Cui, G. Hartner, S. Menary, U. Noor, M. Soares, J. Standage,  
J. Whyte

*Department of Physics, York University, Ontario, Canada M3J 1P3<sup>a</sup>*

<sup>1</sup> also affiliated with University College London, UK

<sup>2</sup> now at Siemens VDO/Sensorik, Weissensberg

<sup>3</sup> retired

<sup>4</sup> PPARC Advanced fellow

<sup>5</sup> supported by a scholarship of the World Laboratory Björn Wiik Research Project

<sup>6</sup> partly supported by Polish Ministry of Scientific Research and Information Technology,  
grant no.2P03B 12625

<sup>7</sup> supported by the Polish State Committee for Scientific Research, grant no. 2 P03B  
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<sup>8</sup> now at DESY group FEB, Hamburg, Germany

<sup>9</sup> partly supported by Moscow State University, Russia

<sup>10</sup> also affiliated with DESY

<sup>11</sup> now at CERN, Geneva, Switzerland

<sup>12</sup> now at Baylor University, USA

<sup>13</sup> now at University of Oxford, UK

<sup>14</sup> now at the Department of Physics and Astronomy, University of Glasgow, UK

<sup>15</sup> now at Royal Holloway University of London, UK

<sup>16</sup> also at Nara Women's University, Nara, Japan

<sup>17</sup> also at University of Tokyo, Japan

<sup>18</sup> Ramón y Cajal Fellow

<sup>19</sup> PPARC Postdoctoral Research Fellow

<sup>20</sup> EU Marie Curie Fellow

<sup>21</sup> on leave of absence at The National Science Foundation, Arlington, VA, USA

<sup>22</sup> also at Max Planck Institute, Munich, Germany, Alexander von Humboldt Research  
Award

<sup>23</sup> Department of Radiological Science

<sup>24</sup> also at University of Hamburg, Germany, Alexander von Humboldt Fellow

<sup>25</sup> partially funded by DESY

<sup>26</sup> also at Lódź University, Poland

<sup>27</sup> Lódź University, Poland

<sup>28</sup> Lódź University, Poland, supported by the KBN grant 2P03B12925

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# 1 Introduction

Charm and/or jet production in  $ep$  collisions should be accurately calculable in perturbative Quantum Chromodynamics (pQCD) since the mass of the heavy quark,  $m_Q$ , and the transverse energy of the jet,  $E_T^{\text{jet}}$ , provide hard scales. In photoproduction, where a quasi-real photon, emitted from the incoming lepton, collides with a parton from the incoming proton, such events can be classified into two types of process in leading-order (LO) QCD. In direct processes, the photon couples as a point-like object in the hard scatter. In resolved processes, the photon acts as a source of incoming partons with only a fraction of its momentum participating in the hard scatter.

Measurements of the  $D^*$  photoproduction cross section [1] as functions of the transverse momentum,  $p_T^{D^*}$ , and the pseudorapidity,  $\eta^{D^*}$ , show that the predictions from next-to-leading-order (NLO) QCD are too low for  $p_T^{D^*} > 3 \text{ GeV}$  and  $\eta^{D^*} > 0$ . Part of this deficit may be due to hadronisation effects. The predictions for jet production accompanied by a  $D^*$  meson should have smaller uncertainties from these hadronisation effects. Furthermore jets can be measured in a wider pseudorapidity range than  $D^*$  mesons due to the larger acceptance of the calorimeter compared to the central tracker.

A dijet sample of  $D^*$  photoproduction can also be used to study higher-order QCD topologies [1, 2]. In the present paper, previously unmeasured correlations between the two jets of highest transverse energy, namely the difference in azimuthal angle,  $\Delta\phi^{jj}$ , and the squared transverse momentum of the dijet system,  $(p_T^{jj})^2$ , which are particularly sensitive to higher-order topologies, are presented. For the LO  $2 \rightarrow 2$  process, the two jets are produced back-to-back with  $\Delta\phi^{jj} = \pi$  and  $(p_T^{jj})^2 = 0$ . Large deviations from these values may come from higher-order QCD effects. The accuracy of the theoretical description of these effects is tested.

Calculations performed to NLO in QCD are available with two different treatments for charm. In the fixed-order, or “massive”, scheme [3],  $u$ ,  $d$  and  $s$  are the only active flavours in the structure functions of the proton and photon; charm and beauty are produced only in the hard scatter. This scheme is expected to work well in regions where the transverse momentum of the outgoing  $c$  quark is of the order of the quark mass. At higher transverse momenta, the resummed or “massless” scheme [4, 5] should be applicable. In this scheme, charm and beauty are regarded as active flavours (massless partons) in the structure functions of the proton and photon and are fragmented from massless partons into massive hadrons after the hard process.

In this paper, photoproduction of charm is studied by tagging a  $D^{*\pm}$  meson and reconstructing at least one jet in the final state. The measurement is performed in the following kinematic region: photon virtuality,  $Q^2 < 1 \text{ GeV}^2$ ; photon-proton centre-of-mass energy,  $130 < W_{\gamma p} < 280 \text{ GeV}$ ;  $p_T^{D^*} > 3 \text{ GeV}$ ;  $|\eta^{D^*}| < 1.5$ ; jet transverse energy,  $E_T^{\text{jet}} > 6 \text{ GeV}$ ; and

jet pseudorapidity,  $-1.5 < \eta^{\text{jet}} < 2.4$ . Differential cross sections as a function of  $E_T^{\text{jet}}$  and  $\eta^{\text{jet}}$  have been measured. Jets are divided into two categories: jets of the first category are associated with the  $D^*$  meson ( $D^*$ -tagged jet), while jets of the second category are not matched to a  $D^*$  meson (untagged jet). The inclusive,  $D^*$ -tagged and untagged jet cross sections are compared to the massive NLO QCD predictions. A comparison to the massless calculation is only available for the untagged jet cross sections [6].

A sub-sample having at least two jets with  $E_T^{\text{jet}1} > 7 \text{ GeV}$  and  $E_T^{\text{jet}2} > 6 \text{ GeV}$  is used to measure the correlations between the two highest  $E_T^{\text{jet}}$  jets: the fraction of the photon momentum participating in dijet production,  $x_\gamma^{\text{obs}}$  [7];  $\Delta\phi^{jj}$ ;  $(p_T^{jj})^2$ ; and the dijet invariant mass,  $M^{jj}$ . Differential dijet cross sections as a function of these variables have been measured for the direct-enriched ( $x_\gamma^{\text{obs}} > 0.75$ ) and resolved-enriched ( $x_\gamma^{\text{obs}} < 0.75$ ) kinematic regions and compared to massive NLO QCD predictions and Monte Carlo (MC) models.

## 2 Experimental set-up

The analysis was performed with data taken from 1998 to 2000, when HERA collided electrons or positrons<sup>1</sup> with energy  $E_e = 27.5 \text{ GeV}$  with protons of energy  $E_p = 920 \text{ GeV}$  resulting in a centre-of-mass energy of  $318 \text{ GeV}$ . The results are based on an integrated luminosity of  $78.6 \text{ pb}^{-1}$  of  $ep$  collision data taken by the ZEUS detector. A detailed description of the ZEUS detector can be found elsewhere [8]. A brief outline of the components that are most relevant for this analysis is given below.

Charged particles are tracked in the central tracking detector (CTD) [9], which operates in a magnetic field of  $1.43 \text{ T}$  provided by a thin superconducting coil. The CTD consists of 72 cylindrical drift chamber layers, organised in 9 superlayers covering the polar-angle<sup>2</sup> region  $15^\circ < \theta < 164^\circ$ . The transverse-momentum resolution for full-length tracks is  $\sigma(p_T)/p_T = 0.0058p_T \oplus 0.0065 \oplus 0.0014/p_T$ , with  $p_T$  in  $\text{GeV}$ .

The high-resolution uranium–scintillator calorimeter (CAL) [10] consists of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part is subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections (HAC). The smallest subdivision of the calorimeter is called a cell. The CAL energy resolutions, as measured under test-beam conditions, are  $\sigma(E)/E = 0.18/\sqrt{E}$  for electrons and  $\sigma(E)/E = 0.35/\sqrt{E}$  for hadrons ( $E$  in  $\text{GeV}$ ).

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<sup>1</sup> Hereafter, both electrons and positrons are referred to as electrons, unless explicitly stated otherwise.

<sup>2</sup> The ZEUS coordinate system is a right-handed Cartesian system, with the  $Z$  axis pointing in the proton beam direction, referred to as the “forward direction”, and the  $X$  axis pointing left towards the center of HERA. The coordinate origin is at the nominal interaction point.

The luminosity was measured from the rate of the bremsstrahlung process  $ep \rightarrow e\gamma p$ , where the photon was measured in a lead–scintillator calorimeter [11] placed in the HERA tunnel at  $Z = -107$  m.

### 3 Event reconstruction and selection

A three-level trigger system was used to select events online [8, 12]. At the first- and second-level triggers, general characteristics of photoproduction events were required and background due to beam-gas interactions rejected. At the third level, a  $D^*$  candidate was reconstructed.

In the offline analysis, the hadronic final state and jets were reconstructed using a combination of track and calorimeter information that optimises the resolution of reconstructed kinematic variables [13]. The selected tracks and calorimeter clusters are referred to as Energy Flow Objects (EFOs). To select photoproduction events, the following criteria were used:

- the event vertex was required to be within 50 cm of the nominal vertex position in the longitudinal direction;
- deep inelastic scattering (DIS) events with a scattered electron candidate in the CAL were removed [14]. To keep the events where a pion was misidentified as a scattered electron, events where  $y_e = 1 - \frac{E_{e'}}{2E_e}(1 - \cos\theta_{e'}) > 0.7$  were retained;  $E_{e'}$  and  $\theta_{e'}$  are the energy and polar angle, respectively, of the scattered electron candidate;
- the requirement  $130 < W_{JB} < 280$  GeV was imposed, where  $W_{JB} = \sqrt{4E_p E_e y_{JB}}$  and  $y_{JB}$  is the estimator of the inelasticity,  $y$ , measured from the EFOs according to the Jacquet-Blondel method [15]. Here,  $W_{JB}$  was corrected, using MC simulation, for the energy losses of EFOs in inactive material in front of the CAL. The upper cut removed DIS events where the scattered electron was not identified and which, therefore, have a value of  $y_{JB}$  close to 1. The lower cut removed proton beam-gas events which have a low value of  $y_{JB}$ .

The cuts on  $y_e$  and  $W_{JB}$  restricted the range of the virtuality of the exchanged photon to  $Q^2$  less than about 1 GeV $^2$ , with a median value of about  $3 \times 10^{-4}$  GeV $^2$ .

#### 3.1 $D^*$ reconstruction

The  $D^*$  mesons were identified using the decay channel  $D^{*+} \rightarrow D^0 \pi_s^+$  with the subsequent decay  $D^0 \rightarrow K^- \pi^+$  and the corresponding antiparticle decay, where  $\pi_s^+$  refers to a low-momentum (“slow”) pion accompanying the  $D^0$ .

Charged tracks measured by the CTD and assigned to the primary event vertex were selected. The transverse momentum was required to be greater than 0.12 GeV. Each track was required to reach at least the third superlayer of the CTD. These restrictions ensured that the track acceptance and momentum resolution were high. Tracks in the CTD with opposite charges and transverse momenta  $p_T > 0.4$  GeV were combined in pairs to form  $D^0$  candidates. The tracks were alternately assigned the masses of a kaon and a pion and the invariant mass of the pair,  $M_{K\pi}$ , was evaluated. Each additional track, with charge opposite to that of the kaon track, was assigned the pion mass and combined with the  $D^0$ -meson candidate to form a  $D^*$  candidate.

The signal regions for the reconstructed masses,  $M(D^0)$  and  $\Delta M = (M_{K\pi\pi_s} - M_{K\pi})$ , were  $1.80 < M(D^0) < 1.92$  GeV and  $0.143 < \Delta M < 0.148$  GeV, respectively. For background determination,  $D^0$  candidates with wrong-sign combinations, in which both tracks forming the  $D^0$  candidates have the same charge and the third track has the opposite charge, were also retained. The same kinematic restrictions were applied as for those  $D^0$  candidates with correct-charge combinations. The normalisation factor of the wrong-charge sample was determined as the ratio of events with correct-charge combinations to wrong-charge combinations in the region  $0.15 < \Delta M < 0.17$  GeV.

The kinematic region for  $D^*$  candidates was  $p_T^{D^*} > 3$  GeV and  $|\eta^{D^*}| < 1.5$ . Figure 1 shows  $\Delta M$  for the selection of a  $D^*$  meson with a jet (see Section 3.2). The fit to the distribution has the form

$$F = p_1 \cdot \exp\left(-0.5 \cdot x^{1+\frac{1}{1+0.5x}}\right) + p_4 \cdot (\Delta M - m_\pi)^{p_5},$$

where  $x = |(\Delta M - p_2)/p_3|$ ,  $p_1 - p_5$  are free parameters and  $m_\pi$  is the pion mass. The “modified” Gaussian described both data and MC distributions well. The fit gives a peak at  $145.467 \pm 0.015$ (stat.) MeV to be compared to the PDG value of  $145.421 \pm 0.010$  MeV [16]. The difference is due to systematic effects which are too small to be relevant for this analysis. The fitted width of  $0.61 \pm 0.02$  MeV is consistent with the experimental resolution.

The number of  $D^*$  mesons was determined from candidates reconstructed in both signal regions and after the subtraction of the background estimated from the wrong-charge sample; this gave  $4891 \pm 113$   $D^*$  mesons. This procedure was used throughout the paper with the number of  $D^*$  mesons obtained from the fit used as a systematic check.

### 3.2 Jet reconstruction

Jets were reconstructed using EFOs as input to the the  $k_T$  cluster algorithm [17] in its longitudinally invariant inclusive mode [18]. The transverse energy of the jet was corrected

for energy losses in inactive material in front of the CAL, where the correction factors were determined in bins of  $E_T^{\text{jet}}$  and  $\eta^{\text{jet}}$  from MC simulation. These corrections were between 5% and 12%.

For the inclusive jet cross sections, jets with  $E_T^{\text{jet}} > 6 \text{ GeV}$  and  $-1.5 < \eta^{\text{jet}} < 2.4$  were selected, and events containing at least one such jet were used for further analysis. For the dijet analysis, events were required to have at least two jets with  $-1.5 < \eta^{\text{jet}} < 2.4$  and  $E_T^{\text{jet}} > 6 \text{ GeV}$ , while the highest  $E_T^{\text{jet}}$  jet was required in addition to satisfy  $E_T^{\text{jet}} > 7 \text{ GeV}$ . The asymmetric jet transverse-energy cut assures that the NLO calculation is not infrared sensitive [19]. After the dijet selection,  $1692 \pm 70$   $D^*$  mesons remained.

Cross sections are given separately for  $D^*$ -tagged and untagged jets.  $D^*$ -tagged jets are defined as jets in which a  $D^*$  (in the kinematic region defined in Section 3.1) was clustered into the jet at the hadron level by the  $k_T$  algorithm. All the other jets are called untagged jets. These two classes of jets can be distinguished experimentally by cutting on the distance  $\Delta R(D^*, \text{jet}) = \sqrt{(\eta^{D^*} - \eta^{\text{jet}})^2 + (\phi^{D^*} - \phi^{\text{jet}})^2}$  between the  $D^*$  and the jet, where  $\phi^{D^*}$  and  $\phi^{\text{jet}}$  are the azimuthal angles of the  $D^*$  meson and jet, respectively. Figure 2 shows the distance of the  $D^*$  to all jets in the event for data and MC. The peak at  $\Delta R(D^*, \text{jet}) = 0$  is due to  $D^*$ -tagged jets as indicated by the  $\Delta R(D^*, \text{jet})$  distribution for  $D^*$ -tagged jets for the MC hadron-level predictions also shown in Fig. 2. The broad peak at  $\Delta R(D^*, \text{jet}) \sim 3$  is due to the untagged jets. A cut at  $\Delta R(D^*, \text{jet}) < 0.6$  was used to distinguish experimentally tagged and untagged jets. For the inclusive jet sample, 83% of  $D^*$  mesons were matched to a jet, and for the dijet sub-sample 94% of  $D^*$  mesons were matched to a jet.

## 4 Monte Carlo models

The MC programmes HERWIG 6.301 [20, 21] and PYTHIA 6.156 [22], which implement LO matrix elements followed by parton showers and hadronisation, were used to model the final state. The HERWIG and PYTHIA generators differ in the details of the implementation of the leading-logarithmic parton-shower models. They also use different hadronisation models: HERWIG uses the cluster [23] model and PYTHIA uses the Lund string [24] model. Direct and resolved events were generated separately and in proportion to the cross sections predicted by the MC programme. The relative fraction of charm and beauty events was also generated in proportion to the cross sections predicted by the MC programme. Events were generated using CTEQ5L [25] and GRV-G LO parton density functions (PDF) for the proton and the photon, respectively. The  $c$ -quark and  $b$ -quark masses were set to  $m_c = 1.5 \text{ GeV}$  and  $m_b = 4.75 \text{ GeV}$ , respectively.

The MC programmes were used both to compare with the dijet cross sections, which are

particularly sensitive to the parton-shower models and for calculation of the acceptance and effects of detector response (see Section 6). For all generated events, the ZEUS detector response was simulated in detail using a programme based on GEANT 3.13 [26].

## 5 NLO QCD calculations

There are two NLO QCD calculations available to calculate jet cross sections in charm photoproduction: the massive calculation by Frixione et al. (FMNR) [3] and the massless calculation by Heinrich and Kniehl [6].

### 5.1 Massive calculation

In the massive calculation, the PDF sets used were CTEQ5M1 [25] for the proton and AFG-HO [27] for the photon. The renormalisation scale,  $\mu_R$ , and factorisation scale,  $\mu_F$ , were set to  $\mu = \mu_R = \mu_F = m_T = \sqrt{\langle (p_T^c)^2 \rangle + m_c^2}$ , where  $\langle (p_T^c)^2 \rangle$  is the average squared transverse momentum of the two charm quarks and  $m_c = 1.5\text{ GeV}$ . The fragmentation of the charm quark into a  $D^*$  meson was described by rescaling the  $c$ -quark momentum using the Peterson fragmentation function [28] with  $\epsilon = 0.035 \pm 0.002$  which is taken from an NLO fit to ARGUS data [29]. The fraction of charm quarks hadronising into a  $D^*$  meson was set to 0.235 [30]. The  $k_T$  algorithm was applied to the outgoing partons in the final state of the NLO programme.

The dependence of the NLO prediction on different photon PDFs,  $\mu_R$ ,  $\mu_F$  and  $m_c$  was evaluated by repeating the calculation using different sets of parameters. The upper (lower) bound of the NLO QCD prediction was estimated by setting  $\mu_R = m_T/2$  and  $m_c = 1.3\text{ GeV}$  ( $\mu_R = 2m_T$  and  $m_c = 1.7\text{ GeV}$ ).

An NLO prediction of  $D^*$  production for beauty is not available so this contribution was estimated using a combination of the  $B$  hadron cross section at NLO and  $B$  decays in PYTHIA. The  $p_T$  distributions of the two stable  $B$  hadrons produced in the PYTHIA MC programme were reweighted to the distribution in the NLO calculation. In the NLO calculation, the  $b$ -quark mass,  $m_b$ , was set to  $4.75\text{ GeV}$ ,  $\mu = m_T = \sqrt{\langle (p_T^b)^2 \rangle + m_b^2}$  and  $\epsilon = 0.0035$  [31]. The branching  $b \rightarrow D^*$  was set to the value measured by the OPAL Collaboration [32]. The upper (lower) bound of the NLO QCD prediction was estimated by setting  $\mu_R = m_T/2$  and  $m_b = 4.5\text{ GeV}$  ( $\mu_R = 2m_T$  and  $m_c = 5.0\text{ GeV}$ ). The contribution from beauty production for the inclusive jet distribution, as predicted by NLO+PYTHIA, is about 2% at low  $E_T^{\text{jet}}$  and increases to 8% at high  $E_T^{\text{jet}}$ . For each cross section, this beauty contribution and its uncertainty were added linearly to the corresponding massive  $D^*$  prediction from charm quarks.

## 5.2 Massless calculation

In the massless calculation, AFG04 [33] for the photon PDF and MRST03 [34] for the proton PDF were used. The number of flavours was set to five. The  $D^*$  fragmentation function and fraction of beauty and charm hadronising into a  $D^*$  meson are derived [5, 6] from a fit to data from LEP; the function is assumed to be applicable to HERA as it is derived using the factorisation theorem in QCD. The central prediction uses  $\mu_R = m'_T = \sqrt{(p_T^{D^*})^2 + m_c^2}$ , where  $m_c = 1.5$  GeV. The fragmentation factorisation [6] scale,  $M_F$ , and  $\mu_F$  were set to  $M_F = \mu_F = 2m'_T$ .

The uncertainty was estimated by changing the scales to  $\mu_R = m'_T/2$  and  $\mu_F = M_F = 4m'_T$  for the upper bound, and  $\mu_R = 2m'_T$  and  $\mu_F = M_F = m'_T$  for the lower bound. The photon PDF, GRV-HO, was used, and the uncertainty was found to be less than half that from the variation in scale [6]. The difference between MRST01 and MRST03 proton PDFs was found to be negligible for the distributions considered. The size of the beauty contribution was estimated by suppressing the final-state fragmentation of a  $b$  quark to a  $D^*$  meson. This reduces the cross-section prediction by about 3% at low  $E_T^{\text{jet}}$  and 15% at high  $E_T^{\text{jet}}$ . Due to theoretical limitations, the predictions for the massless scheme can only be calculated for the untagged-jet distributions.

## 5.3 Hadronisation correction

As the NLO calculations produce final-state partons, the effects of hadronisation were considered when comparing the predictions with the data. The NLO QCD jet predictions were corrected using a bin-by-bin procedure according to  $d\sigma = d\sigma^{\text{NLO}} \cdot C_{\text{had}}$ , where  $d\sigma^{\text{NLO}}$  is the cross section for parton jets in the final state of the NLO calculation. The hadronisation correction factor was defined as the ratio of the jet cross sections after and before the hadronisation process,  $C_{\text{had}} = d\sigma_{\text{MC}}^{\text{hadrons}} / d\sigma_{\text{MC}}^{\text{partons}}$ . Here, parton-level cross sections were obtained using partons after the initial- and final-state showering of the MC simulations described in Section 4. Distributions at the parton level in the MC programmes were checked to be similar to those calculated using the NLO programme, assuring the validity of using a bin-by-bin correction. The value of  $C_{\text{had}}$  was taken as the mean of the ratios obtained using the HERWIG and PYTHIA predictions. The uncertainty on this value was estimated as half the difference between the values obtained using the two models. These uncertainties were added in quadrature to the other uncertainties of the NLO calculations. The values of  $C_{\text{had}}$  applied to the NLO predictions are given in Tables 1–11.

## 6 Data correction and systematic uncertainties

The data were corrected, using the MC models described in Section 4, for the detector acceptance and the selection efficiencies to obtain differential cross sections for the process  $ep \rightarrow e' + D^* + \text{jet(s)} + X$ . The definition of the cross section includes events with a  $D^*$  containing primary  $c$  quarks or those from  $b$ -quark decays. The data were initially compared to the MC simulation in shape and found generally to agree well for all the kinematic quantities. Since HERWIG gives a better overall description of the data than PYTHIA, it was chosen as the primary MC model to correct the data. The cross section for a given observable  $Y$  was determined using

$$\frac{d\sigma}{dY} = \frac{N}{A \cdot \mathcal{L} \cdot B \cdot \Delta Y},$$

where  $N$  is either the number of jets for the inclusive jet cross sections or the number of  $D^*$  mesons for the dijet cross sections in a bin of size  $\Delta Y$ . The acceptance,  $A$ , takes into account migrations and efficiencies for that bin, and  $\mathcal{L}$  is the integrated luminosity. The product,  $B$ , of the appropriate branching ratios for the  $D^*$  and  $D^0$  was set to  $(2.57 \pm 0.06)\%$  [16].

The systematic uncertainties of the measured cross sections were determined by changing the selection cuts or the analysis procedure in turn and repeating the extraction of the cross sections. The uncertainties are described in more detail elsewhere [35]. The following systematic studies have been carried out (the resulting uncertainty on the total cross section is given in parentheses):

- varying the values of the selection cuts by the experimental resolutions in the corresponding quantity ( $^{+2.7\%}_{-2.3\%}$ );
- varying the efficiencies of the CAL first-level trigger (+4.1%);
- the acceptance was recalculated by re-weighting the prediction from the HERWIG MC simulation in  $p_T^{D^*}/E_T^{\text{jet}}$  to reproduce the distribution of this variable in the data (+5.0%);
- an additional contribution to the uncertainty from the modelling of the hadronisation process was estimated by using PYTHIA instead of HERWIG (+0.4%);
- the effect of the uncertainty of the beauty cross section on the acceptance correction was taken into account by increasing the beauty contribution by a factor two ( $< \pm 1\%$ );
- varying the procedure to extract the  $D^*$  signal ( $^{+1.3\%}_{-2.9\%}$ );
- varying by  $\pm 3\%$  the jet energy scale in the CAL ( $^{+2.7\%}_{-2.5\%}$ ).

All systematic uncertainties were added in quadrature to obtain the total systematic uncertainty, except for the jet energy-scale uncertainty, as this has a large correlation between bins, and is shown separately in all figures. In most bins of the differential cross sections, the total systematic uncertainty is comparable to the statistical errors. In addition, an overall normalisation uncertainty of 2% from the luminosity determination is included in neither the figures nor the tables.

## 7 Inclusive jet cross sections

Inclusive jet cross sections with a  $D^*$  in the final state have been measured as a function of  $E_T^{\text{jet}}$  and  $\eta^{\text{jet}}$  in the following kinematic region:

- $Q^2 < 1 \text{ GeV}^2$  and  $130 < W_{\gamma p} < 280 \text{ GeV}$ ;
- $p_T^{D^*} > 3 \text{ GeV}$  and  $|\eta^{D^*}| < 1.5$ ;
- $E_T^{\text{jet}} > 6 \text{ GeV}$  and  $-1.5 < \eta^{\text{jet}} < 2.4$ ;
- a  $D^*$ -jet match is required only where explicitly stated.

At the hadron level, the  $D^*$  meson is used as input into the jet finder therefore allowing a  $D^*$ -tagged jet to be identified unambiguously.

The cross-sections  $d\sigma/dE_T^{\text{jet}}$  in bins of  $\eta^{\text{jet}}$  are shown in Fig. 3 and given in Table 1 for all jets and in Fig. 4 and Table 3 for the whole  $\eta^{\text{jet}}$  range for  $D^*$ -tagged and untagged jets. The distributions tend to fall less steeply with increasing  $\eta^{\text{jet}}$ . The cross sections  $d\sigma/d\eta^{\text{jet}}$  in different regions of  $E_T^{\text{jet}}$  are shown in Fig. 5 and given in Table 2 for all jets and in Fig. 6 and Tables ?? and ?? for  $D^*$ -tagged and untagged jets. Due to the requirement  $|\eta^{D^*}| < 1.5$ , the  $D^*$ -tagged jet is centred around  $\eta^{\text{jet}} = 0$  and falls off rapidly at large  $\eta^{\text{jet}}$ . The advantage of reconstructing jets is observed in the untagged-jet distribution where a significant cross section is measured up to  $\eta^{\text{jet}} = 2.4$ . This is due to the larger acceptance of the CAL compared to the CTD.

The massive calculation is compared to all measured cross sections whereas the massless calculation is compared only to the untagged-jet distributions. The normalisation of the data for all distributions is well described by the upper limit of both NLO QCD predictions. The shape of the data is well described by the NLO QCD predictions. The inclusion of hadronisation corrections which shift the distributions towards forward  $\eta^{\text{jet}}$  improves the description of the data. Some difference in shape is observed for the upper bound of the massless prediction compared to the untagged-jet distributions for  $E_T^{\text{jet}} > 9 \text{ GeV}$  (see Fig. 6).

Measurements of  $d\sigma/dE_T^{\text{jet}}$  and  $d\sigma/d\eta^{\text{jet}}$  in bins of  $p_T^{D^*}$  are given in Tables 5 and 6 and shown in Fig. 7 compared to the massive NLO prediction. The NLO prediction gives a

poor description of the normalisation of the data at lowest  $p_T^{D^*}$ . However, the normalisation of the NLO prediction agrees with the data in the two regions of higher  $p_T^{D^*}$ . In all regions, the shape of the data is reasonably well described by the NLO prediction. Similar conclusions on the normalisation were seen for inclusive  $D^*$  measurements [1]. However, the difference in shape observed as a function of  $\eta^{D^*}$  in the inclusive measurement is not seen here as a function of  $\eta^{\text{jet}}$ . The  $b$ -quark contribution is largest in the region of low  $p_T^{D^*}$ .

In order to be sensitive to higher-order effects, and to distinguish between direct-enriched and resolved-enriched regions, the variable  $x_\gamma^{\text{obs}}(D^*, \text{jet})$  was constructed [6], in an analogous way to the ‘traditional’  $x_\gamma^{\text{obs}}$  [7]. Using the  $D^*$  meson and the untagged jet of highest  $E_T^{\text{jet}}$ , the quantity  $x_\gamma^{\text{obs}}(D^*, \text{jet})$  is given by:

$$x_\gamma^{\text{obs}}(D^*, \text{jet}) = \frac{p_T^{D^*} e^{-\eta^{D^*}} + E_T^{\text{(un>tagged jet)}} e^{-\eta^{\text{(un>tagged jet)}}}}{2yE_e} . \quad (1)$$

This variable has the advantage of being calculable in the massless scheme. In addition it takes advantage of increased statistics by requiring only one jet of high  $E_T^{\text{jet}}$ . In Fig. 8 the measured cross-section  $d\sigma/dx_\gamma^{\text{obs}}(D^*, \text{jet})$ , given in Table 7, is compared to both the massless and massive predictions. The upper bound of the massive prediction gives a good description of the data; the description of the massless prediction is somewhat worse. The HERWIG MC model gives a poor description whilst PYTHIA gives a reasonable description of the shape of the data distribution. Both MC programmes underestimate the normalisation of the data.

## 8 Dijet cross sections

Dijet correlations are particularly sensitive to higher-order effects and therefore suitable to test the limitations of fixed-order perturbative QCD calculations. Events containing a  $D^*$  meson were required to have at least two jets with  $E_T^{\text{jet}1} > 7 \text{ GeV}$ ,  $E_T^{\text{jet}2} > 6 \text{ GeV}$  and  $-1.5 < \eta^{\text{jet}1,2} < 2.4$ . The  $Q^2$ ,  $W_{\gamma p}$ ,  $p_T^{D^*}$  and  $\eta^{D^*}$  requirements were the same as for the inclusive jet cross section.

The dijet variables measured were reconstructed from the two highest  $E_T^{\text{jet}}$  jets as:

$$x_\gamma^{\text{obs}} = \frac{E_T^{\text{jet}1} e^{-\eta^{\text{jet}1}} + E_T^{\text{jet}2} e^{-\eta^{\text{jet}2}}}{2yE_e} , \quad (2)$$

$$\Delta\phi^{\text{jj}} = |\phi^{\text{jet}1} - \phi^{\text{jet}2}| , \quad (3)$$

$$\left(p_T^{jj}\right)^2 = \left(p_x^{\text{jet}1} + p_x^{\text{jet}2}\right)^2 + \left(p_y^{\text{jet}1} + p_y^{\text{jet}2}\right)^2 , \quad (4)$$

$$M^{jj} = \sqrt{2E_T^{\text{jet}1} E_T^{\text{jet}2} [\cosh(\eta^{\text{jet}1} - \eta^{\text{jet}2}) - \cos(\phi^{\text{jet}1} - \phi^{\text{jet}2})]} . \quad (5)$$

Table 8 gives, and Fig. 9a shows, the dijet cross section as a function of  $x_\gamma^{\text{obs}}$ , which is reasonably well described by the massive calculation. In Tables 9-11 and Figs. 9b-d, the cross sections as a function of  $\Delta\phi^{jj}$ ,  $(p_T^{jj})^2$  and  $M^{jj}$  are also shown. For  $\Delta\phi^{jj}$  there is agreement between data and the NLO prediction at large angular separation, but at smaller  $\Delta\phi^{jj}$  values the NLO prediction underestimates the data. This is correlated with the agreement and disagreement at low and high  $(p_T^{jj})^2$  values, respectively. The distribution in dijet invariant mass is described well by the upper limit of the NLO prediction, as was the case for the inclusive jet cross sections in Section 7.

Cross sections as a function of  $M^{jj}$ ,  $\Delta\phi^{jj}$  and  $(p_T^{jj})^2$  are shown in Figs. 10–12 and given in Tables 9-11 separately for direct-enriched ( $x_\gamma^{\text{obs}} > 0.75$ ) and resolved-enriched ( $x_\gamma^{\text{obs}} < 0.75$ ) samples. The data are compared to massive NLO QCD predictions and expectations from MC models.

The cross-section  $d\sigma/dM^{jj}$  in Fig. 10 is described well by the NLO prediction and both MC models, HERWIG and PYTHIA, for both regions in  $x_\gamma^{\text{obs}}$ .

The cross-sections  $d\sigma/d\Delta\phi^{jj}$  (see Fig. 11) and  $d\sigma/d(p_T^{jj})^2$  (see Fig. 12) are reasonably well reproduced by the NLO prediction for  $x_\gamma^{\text{obs}} > 0.75$  although the data exhibit a somewhat harder distribution. For  $x_\gamma^{\text{obs}} < 0.75$ , the data exhibit a harder spectrum than for  $x_\gamma^{\text{obs}} > 0.75$ . The NLO prediction of the cross section for  $x_\gamma^{\text{obs}} < 0.75$  has a significantly softer distribution compared to the data, both as a function of  $\Delta\phi^{jj}$  and  $(p_T^{jj})^2$ . The low- $x_\gamma^{\text{obs}}$  region is more sensitive to higher-order topologies not present in the massive NLO calculation. The predictions from the PYTHIA MC reproduce neither the shape nor the normalisation of the data for low and high  $x_\gamma^{\text{obs}}$ . However, the predictions from the HERWIG MC give an excellent description of the shapes of all distributions, although the normalisation is underestimated by a factor of 2.5. The fact that a MC programme incorporating parton showers can successfully describe the data whereas the NLO QCD prediction cannot indicates that the QCD calculation requires higher orders. Matching of parton showers with NLO calculations such as in the MC@NLO programme [36], which is not currently available for the processes studied here, should improve the description of the data.

## 9 Conclusions

Differential inclusive jet cross sections for events containing a  $D^*$  meson have been measured with the ZEUS detector in the kinematic region  $Q^2 < 1 \text{ GeV}^2$ ,  $130 < W_{\gamma p} < 280 \text{ GeV}$ ,  $p_T^{D^*} > 3 \text{ GeV}$ ,  $|\eta^{D^*}| < 1.5$ ,  $E_T^{\text{jet}} > 6 \text{ GeV}$  and  $-1.5 < \eta^{\text{jet}} < 2.4$ . The measurements are compared to NLO QCD predictions in the massive and massless schemes. With the addition of hadronisation corrections, the upper limit of both theoretical predictions show similar trends and reasonable agreement with all measured cross sections. Dijet correlation cross-sections  $d\sigma/dM_{\gamma j}^{\text{jj}}$  and  $d\sigma/dx_\gamma^{\text{obs}}$  are well described by the massive NLO QCD prediction, although again the data tends to agree better with the upper bound of the NLO calculation. In contrast, the cross-sections  $d\sigma/d\Delta\phi_{\gamma j}^{\text{jj}}$  and  $d\sigma/d(p_T^{\text{jj}})^2$  show a large deviation from the massive NLO QCD prediction at low  $\Delta\phi_{\gamma j}^{\text{jj}}$  and high  $(p_T^{\text{jj}})^2$ . This discrepancy is enhanced for the resolved-enriched ( $x_\gamma^{\text{obs}} < 0.75$ ) sample. These regions are expected to be particularly sensitive to higher-order effects. The HERWIG MC model which incorporates leading-order matrix elements followed by parton showers and hadronisation describes the shape of the measurements well. This indicates that for the precise description of charm dijet photoproduction, higher-order calculations or the implementation of additional parton showers in current NLO calculations are needed.

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$\eta^{\text{jet}}$	range	$E_T^{\text{jet}}$	range	$d\sigma/dE_T^{\text{jet}}$	± stat.	± syst.	± E-scale	(nb/GeV)
-1.5	2.4	6.0	9.0	1.583	±0.039	+0.145 -0.079	+0.072 -0.060	
		9.0	13.0	0.367	±0.018	+0.038 -0.017	+0.025 -0.023	
		13.0	18.0	0.0775	±0.0092	+0.0147 -0.0073	+0.0097 -0.0074	
		18.0	25.0	0.0269	±0.0046	+0.0053 -0.0055	+0.0032 -0.0026	
-1.5	-0.5	6.0	9.0	0.321	±0.017	+0.032 -0.010	+0.025 -0.018	
		9.0	13.0	0.0408	±0.0062	+0.0053 -0.0039	+0.0044 -0.0044	
		13.0	18.0	0.0088	±0.0033	+0.0013 -0.0055	+0.0020 -0.0022	
		18.0	25.0	0.00	±0.00	+0.00 0.00	+0.00 0.00	
-0.5	0.5	6.0	9.0	0.669	±0.023	+0.064 -0.033	+0.027 -0.023	
		9.0	13.0	0.159	±0.011	+0.017 -0.010	+0.011 -0.010	
		13.0	18.0	0.0315	±0.0050	+0.0056 -0.0030	+0.0042 -0.0037	
		18.0	25.0	0.0089	±0.0025	+0.0032 -0.0012	+0.0012 -0.0010	
0.5	1.5	6.0	9.0	0.446	±0.022	+0.048 -0.024	+0.016 -0.013	
		9.0	13.0	0.122	±0.011	+0.015 -0.010	+0.007 -0.006	
		13.0	18.0	0.0306	±0.0063	+0.0110 -0.0032	+0.0034 -0.0020	
		18.0	25.0	0.0126	±0.0033	+0.0032 -0.0047	+0.0013 -0.0014	
1.5	2.4	6.0	9.0	0.151	±0.017	+0.015 -0.026	+0.004 -0.006	
		9.0	13.0	0.0462	±0.0072	+0.0075 -0.0058	+0.0024 -0.0024	
		13.0	18.0	0.0095	±0.0041	+0.0055 -0.0047	+0.0013 -0.0008	
		18.0	25.0	0.0053	±0.0019	+0.0013 -0.0015	+0.0007 0.0002	

**Table 1:** The cross section  $d\sigma/dE_T^{\text{jet}}$  for events containing at least one  $D^*$  meson in different regions of  $\eta^{\text{jet}}$ . The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$E_T^{\text{jet}}$ range	$\eta^{\text{jet}}$ range		$d\sigma/d\eta^{\text{jet}}$	$\pm$ stat.	$\pm$ syst.	$\pm$ E-scale	(nb)
$E_T^{\text{jet}} > 6$	-1.5	-1.0	0.548	$\pm 0.069$	$+0.086$ $-0.156$	$+0.065$ $-0.053$	
	-1.0	-0.5	1.745	$\pm 0.094$	$+0.210$ $-0.059$	$+0.135$ $-0.100$	
	-0.5	0.0	2.79	$\pm 0.12$	$+0.26$ $-0.18$	$+0.16$ $-0.14$	
	0.0	0.5	2.90	$\pm 0.12$	$+0.31$ $-0.11$	$+0.13$ $-0.12$	
	0.5	1.0	2.30	$\pm 0.12$	$+0.28$ $-0.10$	$+0.11$ $-0.09$	
	1.0	1.5	1.85	$\pm 0.13$	$+0.15$ $-0.11$	$+0.08$ $-0.07$	
	1.5	2.0	0.871	$\pm 0.093$	$+0.087$ $-0.082$	$+0.035$ $-0.043$	
	2.0	2.4	0.74	$\pm 0.11$	$+0.07$ $-0.15$	$+0.04$ $-0.03$	
$6 < E_T^{\text{jet}} < 9$	-1.5	-1.0	0.546	$\pm 0.066$	$+0.066$ $-0.111$	$+0.062$ $-0.046$	
	-1.0	-0.5	1.374	$\pm 0.081$	$+0.166$ $-0.043$	$+0.097$ $-0.065$	
	-0.5	0.0	2.067	$\pm 0.097$	$+0.200$ $-0.163$	$+0.098$ $-0.091$	
	0.0	0.5	1.944	$\pm 0.096$	$+0.217$ $-0.094$	$+0.065$ $-0.051$	
	0.5	1.0	1.429	$\pm 0.093$	$+0.184$ $-0.059$	$+0.048$ $-0.040$	
	1.0	1.5	1.30	$\pm 0.10$	$+0.12$ $-0.12$	$+0.05$ $-0.04$	
	1.5	2.0	0.542	$\pm 0.075$	$+0.071$ $-0.080$	$+0.009$ $-0.027$	
	2.0	2.4	0.463	$\pm 0.089$	$+0.051$ $-0.131$	$+0.023$ $-0.011$	
$E_T^{\text{jet}} > 9$	-1.50	-1.00					
	-1.0	-0.5	0.377	$\pm 0.051$	$+0.043$ $-0.054$	$+0.040$ $-0.039$	
	-0.5	0.0	0.727	$\pm 0.070$	$+0.076$ $-0.049$	$+0.067$ $-0.054$	
	0.0	0.5	0.950	$\pm 0.074$	$+0.130$ $-0.045$	$+0.072$ $-0.070$	
	0.5	1.0	0.872	$\pm 0.080$	$+0.132$ $-0.066$	$+0.065$ $-0.050$	
	1.0	1.5	0.559	$\pm 0.079$	$+0.087$ $-0.071$	$+0.032$ $-0.028$	
	1.5	2.0	0.326	$\pm 0.056$	$+0.064$ $-0.043$	$+0.027$ $-0.016$	
	2.0	2.4	0.276	$\pm 0.063$	$+0.049$ $-0.066$	$+0.013$ $-0.019$	

**Table 2:** The cross section  $d\sigma/d\eta^{\text{jet}}$  for events containing at least one  $D^*$  meson in different regions of  $E_T^{\text{jet}}$ . The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$E_T^{\text{jet}}$ range		$d\sigma/dE_T^{\text{jet}}$ $\pm$ stat. $\pm$ syst. $\pm$ E-scale (nb/GeV)							
		$D^*$ -tagged jet				un-tagged jets			
6.00	9.00	0.889	$\pm 0.028$	$+0.135$	$+0.039$	0.704	$\pm 0.028$	$+0.030$	$+0.035$
9.00	13.00	0.208	$\pm 0.012$	$+0.033$	$+0.015$	0.161	$\pm 0.014$	$+0.006$	$+0.010$
13.00	18.00	0.0374	$\pm 0.0059$	$+0.0064$	$+0.0049$	0.0423	$\pm 0.0076$	$+0.0122$	$+0.0049$
18.00	25.00	0.0145	$\pm 0.0034$	$+0.0046$	$+0.0027$	0.0124	$\pm 0.0030$	$+0.0040$	$+0.0007$
				$-0.039$	$-0.028$			$-0.045$	$-0.035$
				$-0.013$	$-0.013$			$-0.006$	$-0.010$
				$-0.0054$	$-0.0035$			$-0.0048$	$-0.0043$
				$-0.0043$	$-0.0022$			$-0.0035$	$-0.0003$

**Table 3:** The cross section  $d\sigma/dE_T^{\text{jet}}$  for  $D^*$ -tagged jets and untagged jets for  $-1.5 < \eta^{\text{jet}} < 2.4$ . The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$\eta^{\text{jet}}$ range		$d\sigma/d\eta^{\text{jet}}$ $\pm$ stat. $\pm$ syst. $\pm$ E-scale (nb)							
		$D^*$ matched jet			other jets				
-1.50	-1.00	0.412	$\pm 0.055$	$+0.060$ $-0.054$	$+0.043$ $-0.034$	0.173	$\pm 0.043$	$+0.058$ $-0.097$	$+0.022$ $-0.015$
-1.00	-0.50	1.170	$\pm 0.075$	$+0.236$ $-0.064$	$+0.089$ $-0.048$	0.560	$\pm 0.075$	$+0.039$ $-0.029$	$+0.035$ $-0.036$
-0.50	0.00	1.831	$\pm 0.097$	$+0.324$ $-0.123$	$+0.084$ $-0.067$	1.010	$\pm 0.094$	$+0.081$ $-0.224$	$+0.053$ $-0.063$
0.00	0.50	1.78	$\pm 0.11$	$+0.34$ $-0.12$	$+0.05$ $-0.04$	1.113	$\pm 0.095$	$+0.099$ $-0.056$	$+0.044$ $-0.044$
0.50	1.00	1.18	$\pm 0.11$	$+0.30$ $-0.08$	$+0.03$ $-0.03$	1.08	$\pm 0.10$	$+0.10$ $-0.07$	$+0.05$ $-0.04$
1.00	1.50	0.99	$\pm 0.13$	$+0.24$ $-0.11$	$+0.02$ $-0.01$	1.014	$\pm 0.098$	$+0.085$ $-0.129$	$+0.054$ $-0.046$
1.50	2.00	0.19	$\pm 0.17$	$+0.22$ $-0.17$	$+0.00$ $-0.02$	0.75	$\pm 0.10$	$+0.10$ $-0.11$	$+0.01$ $-0.04$
2.00	2.40					0.70	$\pm 0.13$	$+0.08$ $-0.20$	$+0.04$ $-0.02$
-1.50	-1.00	0.386	$\pm 0.052$	$+0.051$ $-0.051$	$+0.040$ $-0.032$	0.160	$\pm 0.040$	$+0.055$ $-0.089$	$+0.021$ $-0.014$
-1.00	-0.50	0.935	$\pm 0.060$	$+0.157$ $-0.037$	$+0.071$ $-0.038$	0.438	$\pm 0.058$	$+0.039$ $-0.023$	$+0.027$ $-0.028$
-0.50	0.00	1.367	$\pm 0.073$	$+0.186$ $-0.060$	$+0.063$ $-0.050$	0.714	$\pm 0.067$	$+0.055$ $-0.148$	$+0.037$ $-0.045$
0.00	0.50	1.224	$\pm 0.074$	$+0.182$ $-0.075$	$+0.037$ $-0.024$	0.725	$\pm 0.062$	$+0.065$ $-0.036$	$+0.029$ $-0.028$
0.50	1.00	0.771	$\pm 0.069$	$+0.162$ $-0.050$	$+0.019$ $-0.017$	0.665	$\pm 0.063$	$+0.055$ $-0.039$	$+0.033$ $-0.025$
1.00	1.50	0.651	$\pm 0.086$	$+0.132$ $-0.076$	$+0.015$ $-0.010$	0.623	$\pm 0.061$	$+0.049$ $-0.080$	$+0.033$ $-0.028$
1.50	2.00	0.113	$\pm 0.100$	$+0.154$ $-0.098$	$+0.001$ $-0.013$	0.473	$\pm 0.066$	$+0.064$ $-0.070$	$+0.008$ $-0.022$
2.00	2.40					0.466	$\pm 0.089$	$+0.049$ $-0.131$	$+0.023$ $-0.011$
-1.50	-1.00								
-1.00	-0.50	0.239	$\pm 0.036$	$+0.039$ $-0.023$	$+0.023$ $-0.023$	0.148	$\pm 0.043$	$+0.021$ $-0.091$	$+0.021$ $-0.019$
-0.50	0.00	0.514	$\pm 0.050$	$+0.064$ $-0.047$	$+0.047$ $-0.038$	0.194	$\pm 0.055$	$+0.058$ $-0.015$	$+0.018$ $-0.015$
0.00	0.50	0.620	$\pm 0.055$	$+0.096$ $-0.045$	$+0.051$ $-0.048$	0.328	$\pm 0.051$	$+0.053$ $-0.018$	$+0.020$ $-0.021$
0.50	1.00	0.520	$\pm 0.056$	$+0.118$ $-0.042$	$+0.041$ $-0.026$	0.358	$\pm 0.063$	$+0.038$ $-0.052$	$+0.023$ $-0.026$
1.00	1.50	0.231	$\pm 0.057$	$+0.044$ $-0.041$	$+0.015$ $-0.011$	0.335	$\pm 0.055$	$+0.067$ $-0.039$	$+0.016$ $-0.018$
1.50	2.00	0.140	$\pm 0.080$	$+0.080$ $-0.078$	$+0.022$ $-0.012$	0.263	$\pm 0.048$	$+0.048$ $-0.033$	$+0.021$ $-0.013$
2.00	2.40					0.275	$\pm 0.062$	$+0.049$ $-0.065$	$+0.013$ $-0.019$

**Table 4:** The cross section  $d\sigma/d\eta^{\text{jet}}$  for  $D^*$ -tagged jets and untagged jets for  $E_T^{\text{jet}} > 6 \text{ GeV}$ . The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$p_T(D^*)$ range	$E_T^{\text{jet}}$ range	$d\sigma/dE_T^{\text{jet}}$	$\pm$ stat.	$\pm$ syst.	$\pm$ E-scale	(nb/GeV)
3.25    5.00	6.0    9.0	0.907	$\pm 0.032$	$+0.130$ $-0.042$	$+0.083$ $-0.067$	
	9.0    13.0	0.137	$\pm 0.015$	$+0.018$ $-0.012$	$+0.014$ $-0.013$	
	13.0    18.0	0.0279	$\pm 0.0085$	$+0.0134$ $-0.0055$	$+0.0027$ $-0.0040$	
	18.0    25.0	0.0095	$\pm 0.0047$	$+0.0050$ $-0.0051$	$+0.0006$ $-0.0018$	
5.00    8.00	6.0    9.0	0.510	$\pm 0.016$	$+0.043$ $-0.039$	$+0.004$ $-0.000$	
	9.0    13.0	0.1432	$\pm 0.0091$	$+0.0127$ $-0.0050$	$+0.0142$ $-0.0112$	
	13.0    18.0	0.0200	$\pm 0.0040$	$+0.0060$ $-0.0021$	$+0.0030$ $-0.0017$	
	18.0    25.0	0.0093	$\pm 0.0034$	$+0.0070$ $-0.0038$	$+0.0024$ $-0.0025$	
8.00    20.00	6.0    9.0	0.0377	$\pm 0.0036$	$+0.0021$ $-0.0071$	$+0.0018$ $0.0014$	
	9.0    13.0	0.0731	$\pm 0.0050$	$+0.0016$ $-0.0087$	$+0.0009$ $0.0005$	
	13.0    18.0	0.0338	$\pm 0.0036$	$+0.0021$ $-0.0017$	$+0.0039$ $-0.0031$	
	18.0    25.0	0.0092	$\pm 0.0019$	$+0.0012$ $-0.0012$	$+0.0012$ $-0.0004$	

**Table 5:** The cross section  $d\sigma/dE_T^{\text{jet}}$  in bins of  $p_T^{D^*}$ . The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$p_T(D^*)$	range	$\eta^{\text{jet}}$	range	$d\sigma/d\eta^{\text{jet}}$	± stat.	± syst.	± E-scale	(nb)
3.25	5.00	-1.5	-1.0	0.360	$\pm 0.058$	$+0.074$ $-0.117$	$+0.071$ $-0.051$	
		-1.0	-0.5	0.903	$\pm 0.075$	$+0.282$ $-0.105$	$+0.113$ $-0.083$	
		-0.5	0.0	1.465	$\pm 0.096$	$+0.162$ $-0.184$	$+0.140$ $-0.122$	
		0.0	0.5	1.453	$\pm 0.094$	$+0.207$ $-0.167$	$+0.110$ $-0.103$	
		0.5	1.0	1.063	$\pm 0.097$	$+0.244$ $-0.046$	$+0.094$ $-0.074$	
		1.0	1.5	0.98	$\pm 0.11$	$+0.16$ $-0.20$	$+0.08$ $-0.06$	
		1.5	2.0	0.391	$\pm 0.076$	$+0.078$ $-0.048$	$+0.021$ $-0.025$	
		2.0	2.4	0.335	$\pm 0.092$	$+0.102$ $-0.129$	$+0.018$ $-0.013$	
5.00	8.00	-1.5	-1.0	0.211	$\pm 0.033$	$+0.081$ $-0.051$	$+0.014$ $-0.007$	
		-1.0	-0.5	0.602	$\pm 0.046$	$+0.050$ $-0.030$	$+0.029$ $-0.018$	
		-0.5	0.0	0.981	$\pm 0.056$	$+0.066$ $-0.048$	$+0.030$ $-0.024$	
		0.0	0.5	1.015	$\pm 0.057$	$+0.105$ $-0.074$	$+0.026$ $-0.022$	
		0.5	1.0	0.745	$\pm 0.051$	$+0.107$ $-0.037$	$+0.022$ $-0.016$	
		1.0	1.5	0.534	$\pm 0.053$	$+0.052$ $-0.050$	$+0.018$ $-0.014$	
		1.5	2.0	0.231	$\pm 0.033$	$+0.033$ $-0.018$	$+0.011$ $-0.009$	
		2.0	2.4	0.240	$\pm 0.045$	$+0.035$ $-0.049$	$+0.011$ $-0.009$	
8.0	20.0	-1.50	-1.00					
		-1.0	-0.5	0.101	$\pm 0.020$	$+0.009$ $-0.021$	$+0.001$ $-0.002$	
		-0.5	0.0	0.217	$\pm 0.024$	$+0.010$ $-0.017$	$+0.002$ $-0.002$	
		0.0	0.5	0.274	$\pm 0.027$	$+0.019$ $-0.011$	$+0.002$ $-0.001$	
		0.5	1.0	0.296	$\pm 0.028$	$+0.015$ $-0.036$	$+0.003$ $-0.001$	
		1.0	1.5	0.178	$\pm 0.024$	$+0.008$ $-0.018$	$+0.003$ $-0.003$	
		1.5	2.0	0.108	$\pm 0.021$	$+0.013$ $-0.020$	$+0.000$ $-0.004$	
		2.0	2.4	0.092	$\pm 0.020$	$+0.014$ $-0.019$	$+0.004$ $-0.005$	

**Table 6:** The cross section  $d\sigma/d\eta^{\text{jet}}$  in bins of  $p_T^{D^*}$ . The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$x_\gamma(D^*, \text{jet})$ range		$d\sigma/dx_\gamma(D^*, \text{jet})$	$\pm$ stat.	$\pm$ syst.	$\pm$ E-scale	(nb)
0.000	0.250	1.23	$\pm 0.24$	$+0.13$ $-0.36$	$+0.03$ $-0.06$	
0.250	0.375	2.15	$\pm 0.28$	$+0.37$ $-0.30$	$+0.09$ $-0.11$	
0.375	0.500	2.85	$\pm 0.31$	$+0.36$ $-0.25$	$+0.09$ $-0.10$	
0.500	0.625	3.82	$\pm 0.30$	$+0.46$ $-0.36$	$+0.04$ $-0.06$	
0.625	0.750	5.71	$\pm 0.32$	$+0.23$ $-0.57$	$+0.01$ $-0.09$	
0.750	1.000	2.82	$\pm 0.15$	$+0.25$ $-0.25$	$+0.37$ $-0.30$	

**Table 7:** The cross section  $d\sigma/dx_\gamma^{\text{obs}}(D^*, \text{other jet})$ . The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$x_\gamma^{\text{obs}}$ range		$d\sigma/dx_\gamma^{\text{obs}}$	$\pm$ stat.	$\pm$ syst.	$\pm$ E-scale	(nb)
0.000	0.250	0.19	$\pm 0.15$	$+0.34$ $-0.07$	$+0.02$ $-0.01$	
0.250	0.375	0.78	$\pm 0.22$	$+0.26$ $-0.23$	$+0.08$ $-0.08$	
0.375	0.500	0.99	$\pm 0.19$	$+0.24$ $-0.23$	$+0.08$ $-0.09$	
0.500	0.625	1.52	$\pm 0.22$	$+0.14$ $-0.33$	$+0.12$ $-0.12$	
0.625	0.750	2.03	$\pm 0.24$	$+0.21$ $-0.23$	$+0.18$ $-0.16$	
0.750	1.000	4.35	$\pm 0.21$	$+0.41$ $-0.16$	$+0.28$ $-0.26$	

**Table 8:** The dijet cross section  $d\sigma/dx_\gamma^{\text{obs}}$ , for events containing at least one  $D^*$  meson. The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$\Delta\phi^{jj}$ range		$d\sigma/d\Delta\phi^{jj}$	$\pm$ stat.	$\pm$ syst.	$\pm$ E-scale	(nb/rad.)
$0 < x_\gamma^{\text{obs}} < 1$						
0.00	1.57	0.020	$\pm 0.011$	$+0.012$ $-0.012$	$+0.001$ $-0.003$	
1.57	2.09	0.149	$\pm 0.035$	$+0.051$ $-0.046$	$+0.025$ $-0.014$	
2.09	2.36	0.318	$\pm 0.074$	$+0.057$ $-0.092$	$+0.028$ $-0.029$	
2.36	2.62	0.67	$\pm 0.10$	$+0.17$ $-0.10$	$+0.07$ $-0.05$	
2.62	2.88	1.50	$\pm 0.14$	$+0.18$ $-0.12$	$+0.11$ $-0.11$	
2.88	3.14	4.06	$\pm 0.22$	$+0.39$ $-0.32$	$+0.24$ $-0.23$	
$x_\gamma^{\text{obs}} > 0.75$						
0.00	1.57	0.0158	$\pm 0.0068$	$+0.0058$ $-0.0115$	$+0.0029$ $-0.0017$	
1.57	2.09	0.036	$\pm 0.014$	$+0.006$ $-0.028$	$+0.007$ $-0.003$	
2.09	2.36	0.126	$\pm 0.038$	$+0.032$ $-0.027$	$+0.011$ $-0.012$	
2.36	2.62	0.389	$\pm 0.055$	$+0.077$ $-0.021$	$+0.036$ $-0.028$	
2.62	2.88	0.829	$\pm 0.091$	$+0.105$ $-0.066$	$+0.055$ $-0.055$	
2.88	3.14	2.68	$\pm 0.16$	$+0.28$ $-0.13$	$+0.14$ $-0.13$	
$x_\gamma^{\text{obs}} < 0.75$						
0.00	1.57	0.0066	$\pm 0.0093$	$+0.0141$ $-0.0074$	$+0.0004$ $-0.0010$	
1.57	2.09	0.115	$\pm 0.034$	$+0.049$ $-0.029$	$+0.017$ $-0.012$	
2.09	2.36	0.190	$\pm 0.062$	$+0.042$ $-0.082$	$+0.018$ $-0.018$	
2.36	2.62	0.280	$\pm 0.083$	$+0.157$ $-0.104$	$+0.030$ $-0.020$	
2.62	2.88	0.67	$\pm 0.11$	$+0.10$ $-0.10$	$+0.06$ $-0.06$	
2.88	3.14	1.37	$\pm 0.15$	$+0.14$ $-0.26$	$+0.11$ $-0.10$	

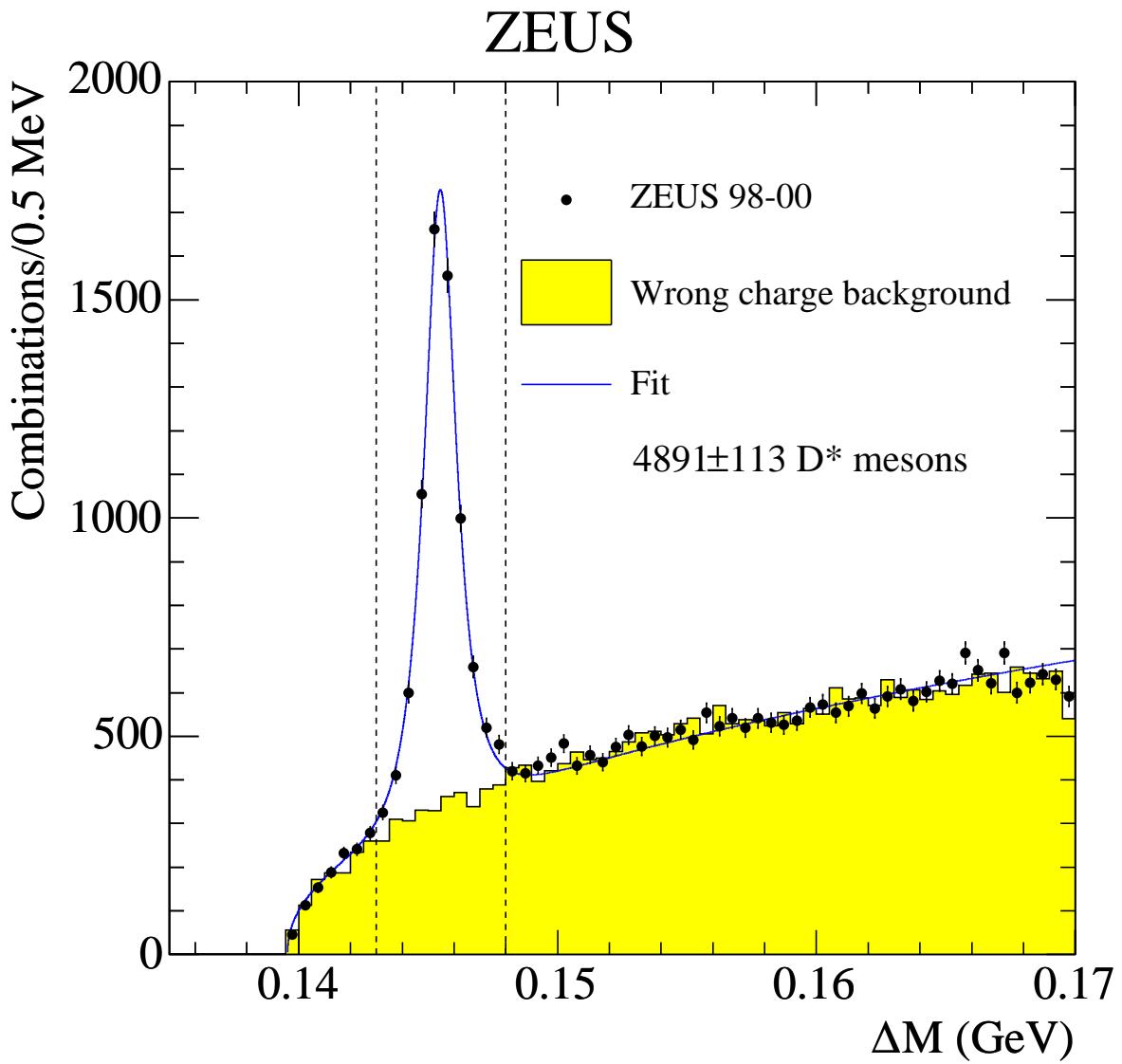
**Table 9:** The dijet cross section  $d\sigma/d\phi^{jj}$ , for events containing at least one  $D^*$  meson for all  $x_\gamma^{\text{obs}}$ , and for direct-enriched ( $x_\gamma^{\text{obs}} > 0.75$ ) and resolved-enriched ( $x_\gamma^{\text{obs}} < 0.75$ ) samples. The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$p_T^{\text{jj}}$ range		$d\sigma/dp_T^{\text{jj}}$	$\pm$ stat.	$\pm$ syst.	$\pm$ E-scale	(nb/GeV)
$0 < x_\gamma^{\text{obs}} < 1$						
0	3	0.282	$\pm 0.018$	$+0.027$ $-0.021$	$+0.021$ $-0.019$	
3	6	0.188	$\pm 0.014$	$+0.033$ $-0.016$	$+0.013$ $-0.013$	
6	9	0.0762	$\pm 0.0095$	$+0.0111$ $-0.0096$	$+0.0048$ $-0.0049$	
9	12	0.0351	$\pm 0.0079$	$+0.0070$ $-0.0127$	$+0.0026$ $-0.0025$	
12	18	0.0109	$\pm 0.0036$	$+0.0037$ $-0.0046$	$+0.0006$ $-0.0001$	
$x_\gamma^{\text{obs}} > 0.75$						
0	3	0.203	$\pm 0.013$	$+0.021$ $-0.018$	$+0.012$ $-0.012$	
3	6	0.1074	$\pm 0.0092$	$+0.0136$ $-0.0090$	$+0.0061$ $-0.0058$	
6	9	0.0300	$\pm 0.0049$	$+0.0060$ $-0.0053$	$+0.0020$ $-0.0018$	
9	12	0.0141	$\pm 0.0045$	$+0.0033$ $-0.0057$	$+0.0019$ $-0.0008$	
12	18	0.0066	$\pm 0.0018$	$+0.0008$ $-0.0040$	$+0.0003$ $0.0003$	
$x_\gamma^{\text{obs}} < 0.75$						
0	3	0.078	$\pm 0.011$	$+0.009$ $-0.014$	$+0.008$ $-0.006$	
3	6	0.082	$\pm 0.011$	$+0.022$ $-0.011$	$+0.008$ $-0.007$	
6	9	0.0479	$\pm 0.0087$	$+0.0099$ $-0.0106$	$+0.0030$ $-0.0033$	
9	12	0.0207	$\pm 0.0063$	$+0.0053$ $-0.0098$	$+0.0008$ $-0.0016$	
12	18	0.0046	$\pm 0.0031$	$+0.0037$ $-0.0025$	$+0.0003$ $-0.0004$	

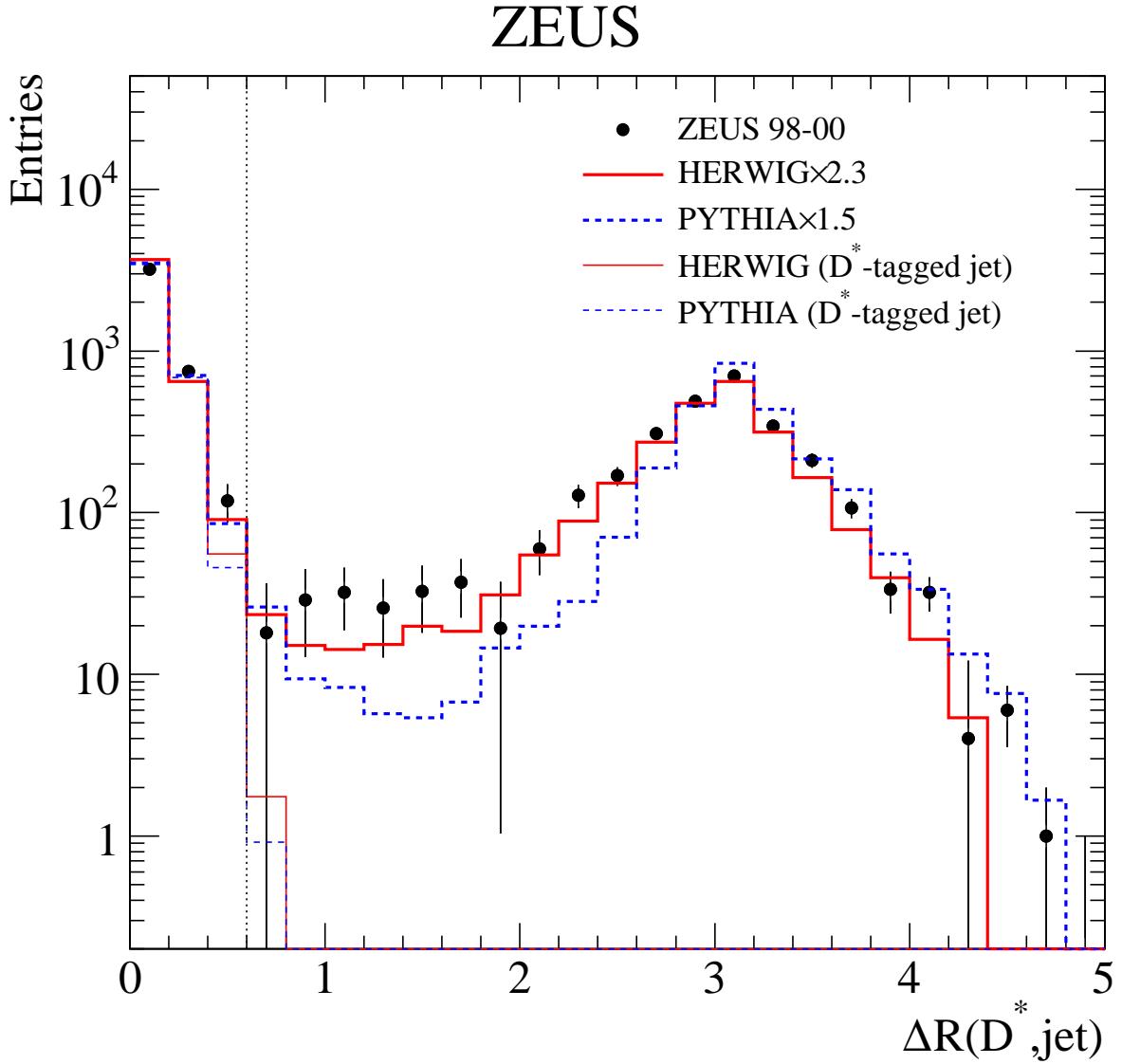
**Table 10:** The dijet cross section  $d\sigma/dp_T^{\text{jj}}$ , for events containing at least one  $D^*$  meson for all  $x_\gamma^{\text{obs}}$ , and for direct-enriched ( $x_\gamma^{\text{obs}} > 0.75$ ) and resolved-enriched ( $x_\gamma^{\text{obs}} < 0.75$ ) samples. The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.

$m^{\text{jj}}$ range		$d\sigma/dm^{\text{jj}}$	± stat.	± syst.	± E-scale	(nb/GeV)
$0 < x_{\gamma}^{\text{obs}} < 1$						
15	20	0.1299	±0.0088	+0.0095 -0.0124	+0.0080 -0.0076	
20	25	0.0823	±0.0076	+0.0082 -0.0076	+0.0060 -0.0059	
25	30	0.0484	±0.0062	+0.0106 -0.0052	+0.0049 -0.0023	
30	35	0.0328	±0.0056	+0.0048 -0.0080	+0.0025 -0.0043	
35	40	0.0223	±0.0048	+0.0018 -0.0054	+0.0033 0.0009	
40	50	0.0081	±0.0022	+0.0017 -0.0016	+0.0006 -0.0010	
$x_{\gamma}^{\text{obs}} > 0.75$						
15	20	0.0788	±0.0056	+0.0064 -0.0065	+0.0033 -0.0035	
20	25	0.0470	±0.0049	+0.0061 -0.0029	+0.0042 -0.0028	
25	30	0.0319	±0.0045	+0.0049 -0.0024	+0.0026 -0.0015	
30	35	0.0221	±0.0045	+0.0042 -0.0045	+0.0018 -0.0031	
35	40	0.0136	±0.0035	+0.0019 -0.0045	+0.0022 0.0003	
40	50	0.0040	±0.0016	+0.0021 -0.0013	+0.0003 -0.0004	
$x_{\gamma}^{\text{obs}} < 0.75$						
15	20	0.0512	±0.0069	+0.0055 -0.0097	+0.0051 -0.0043	
20	25	0.0357	±0.0060	+0.0043 -0.0083	+0.0016 -0.0034	
25	30	0.0166	±0.0041	+0.0059 -0.0036	+0.0023 -0.0008	
30	35	0.0109	±0.0033	+0.0030 -0.0043	+0.0007 -0.0013	
35	40	0.0086	±0.0033	+0.0022 -0.0027	+0.0011 0.0006	
40	50	0.0038	±0.0015	+0.0009 -0.0013	+0.0004 -0.0006	

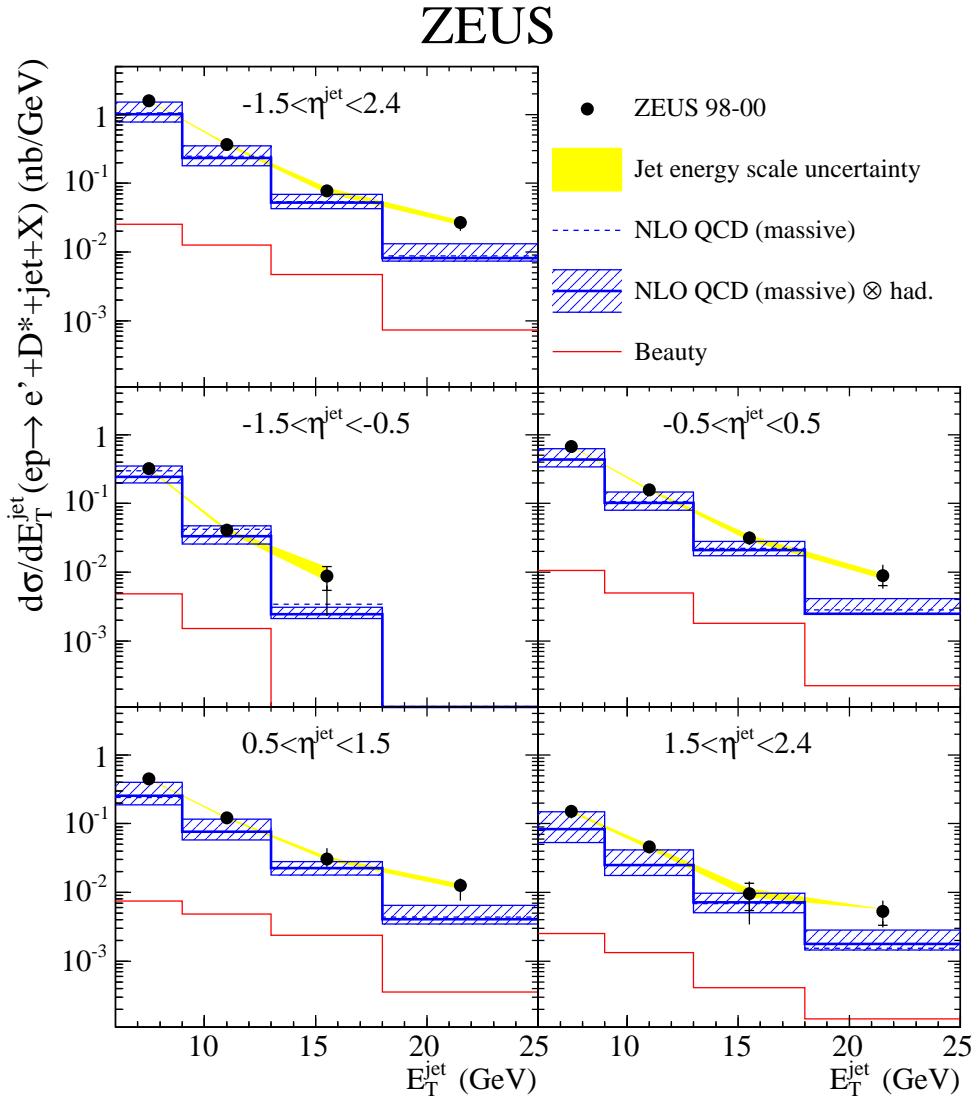
**Table 11:** The dijet cross section  $d\sigma/dM^{\text{jj}}$ , for events containing at least one  $D^*$  meson for all  $x_{\gamma}^{\text{obs}}$ , and for direct-enriched ( $x_{\gamma}^{\text{obs}} > 0.75$ ) and resolved-enriched ( $x_{\gamma}^{\text{obs}} < 0.75$ ) samples. The statistical (stat.), systematic (syst.) and energy scale (E-scale) uncertainties are shown separately.



**Figure 1:** The distribution of the mass difference,  $\Delta M = M(K\pi\pi_s) - M(K\pi)$ , for  $D^*$  candidates with a single jet. The  $D^{*\pm}$  candidates (dots) are shown compared to the wrong charge combinations (histogram). The dashed vertical lines show the signal region,  $0.143 < \Delta M < 0.148$  GeV. The number of  $D^*$  mesons is determined by subtracting the wrong charge background as described in Section 3.1. The fit is for illustrative purposes only.

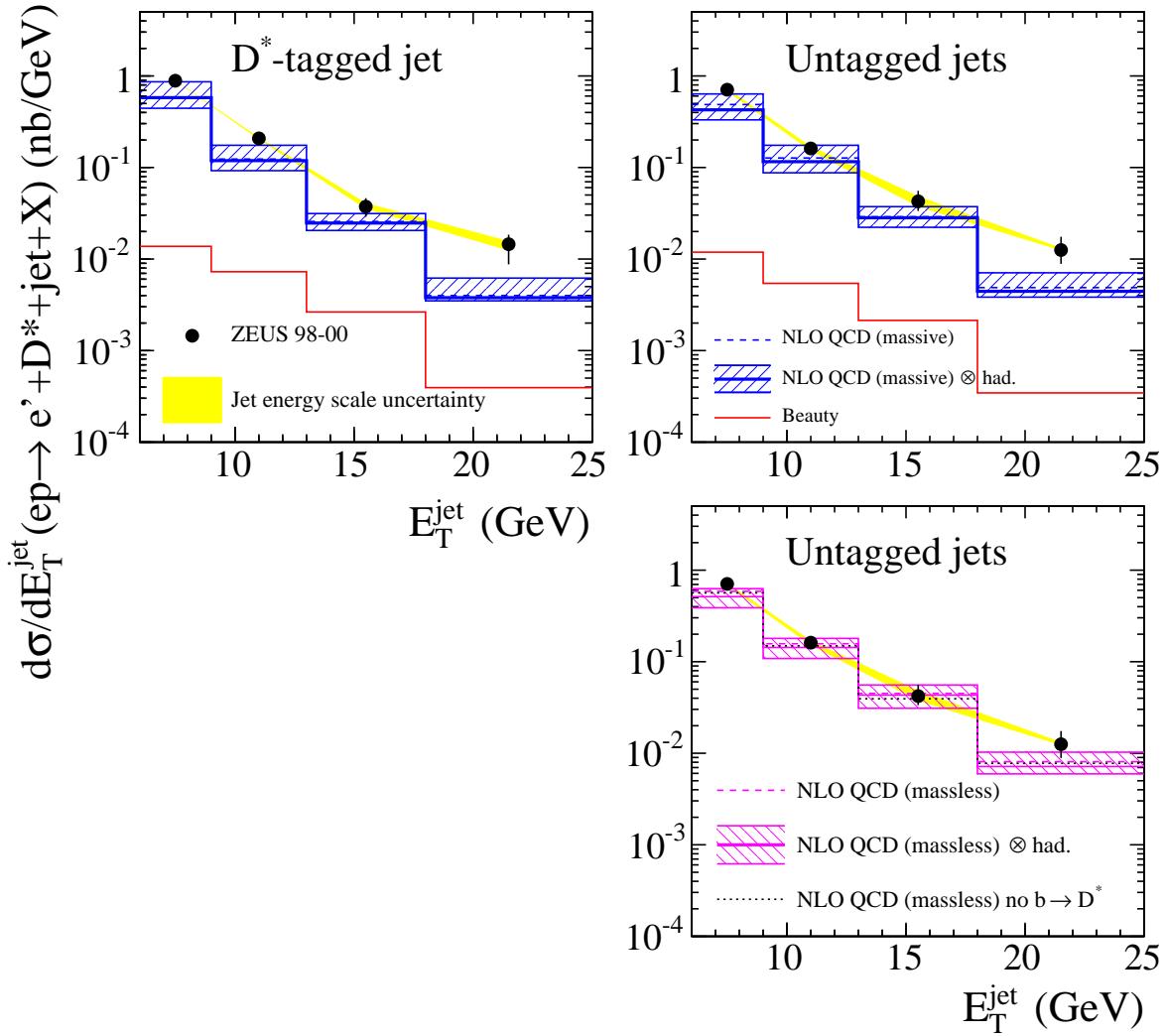


**Figure 2:** The distribution of  $\Delta R$  between  $D^*$  mesons and each jet in the event. The data (dots) are compared to HERWIG (solid line) and PYTHIA (dashed line) MC predictions. The MC predictions are area normalised to the data using the normalisation factors shown in the figure. The dotted vertical line indicates the  $\Delta R = 0.6$  cut which separates  $D^*$ -tagged jets from untagged jets. The  $\Delta R(D^*, \text{jet})$  distribution for  $D^*$ -tagged jets for the MC hadron-level predictions is shown for HERWIG (thin solid line) and PYTHIA (thin dashed line). The hadron-level predictions are area normalised to the data in the region  $\Delta R(D^*, \text{jet}) < 0.6$



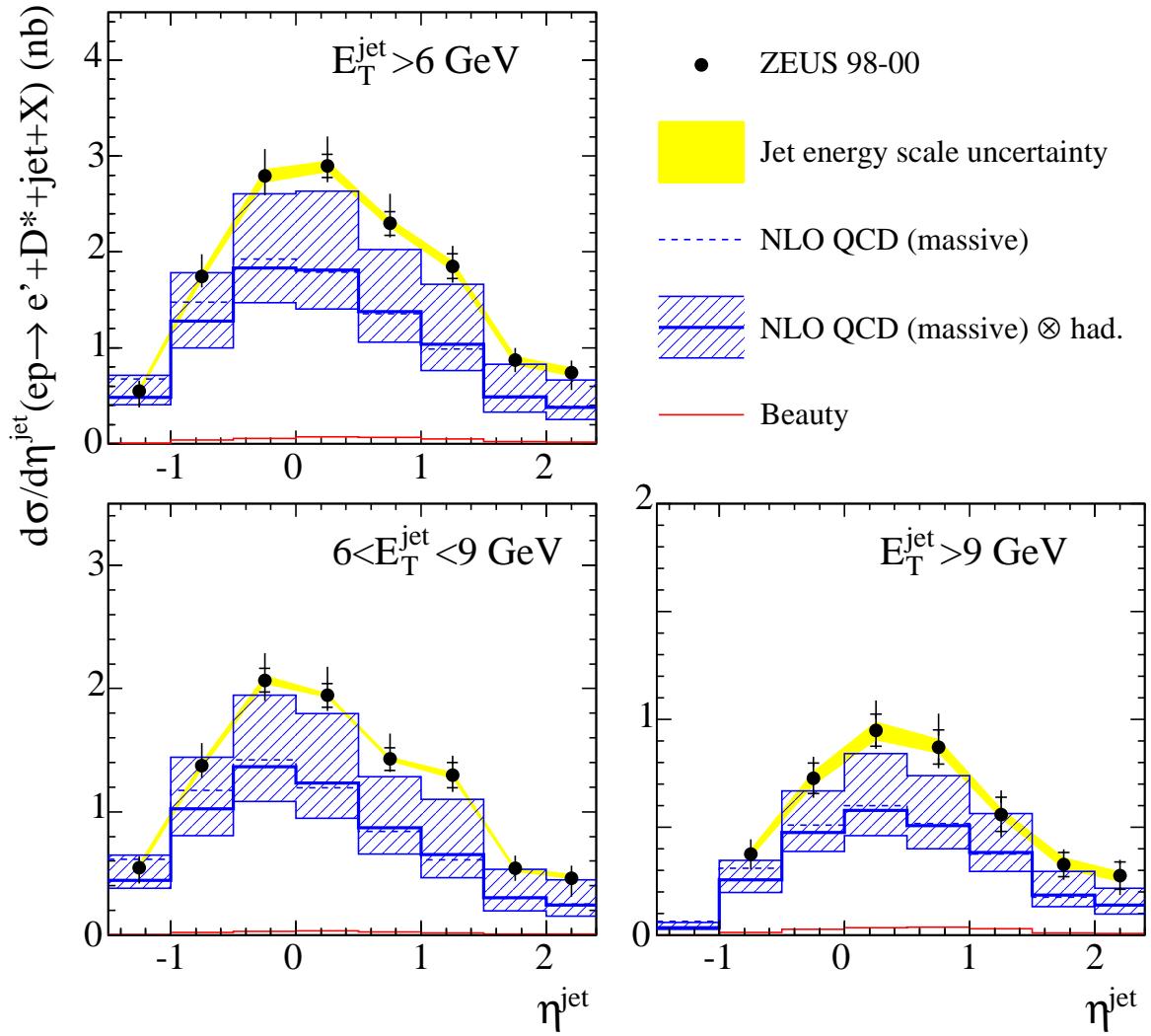
**Figure 3:** Cross-section  $d\sigma/dE_T^{\text{jet}}$  for jets in events (dots) containing at least one  $D^*$  meson for different regions in  $\eta^{\text{jet}}$ . The comparison is made to massive QCD predictions with (solid line) and without (dashed line) hadronisation corrections applied. The theoretical uncertainties (hatched band) come from the change in scales simultaneously with the change in charm mass. The beauty component is also shown (lower histogram).

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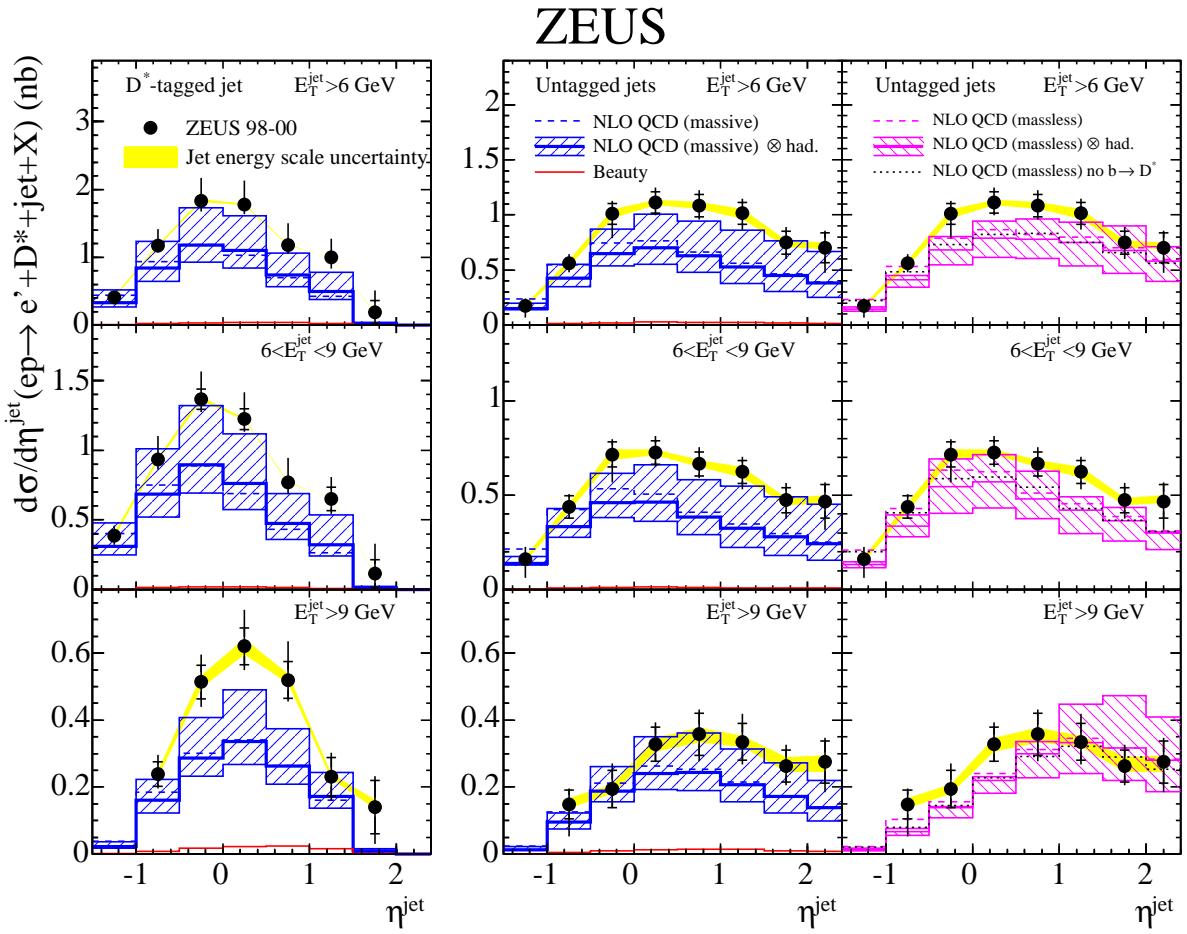


**Figure 4:** Cross-section  $d\sigma/dE_T^{\text{jet}}$  for  $D^*$ -tagged jets and untagged jets (dots). The comparison is made to massive QCD predictions with (solid line) and without (dotted line) hadronisation corrections applied. The beauty component is also shown (lower histogram). For the untagged jet distribution, the massless QCD predictions are also shown with (solid line) and without (dashed line) hadronisation corrections applied. The theoretical uncertainties (hatched bands) come, in the case of the massive calculations, from changing renormalisation and factorisation scales as well as the charm mass simultaneously. In the case of the massless calculations, they come from changing the scales only. The prediction with no component from  $b$ -quark fragmentation to a  $D^*$  is also shown (dotted line).

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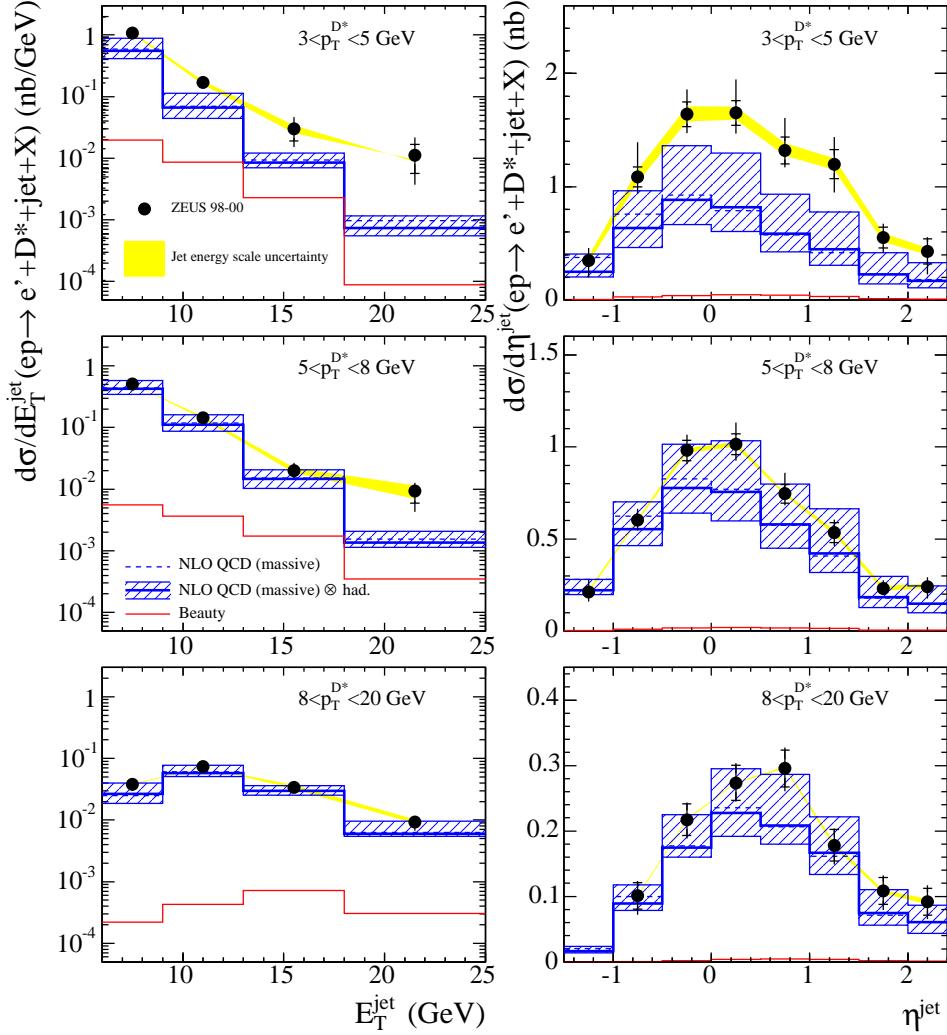


**Figure 5:** Cross-section  $d\sigma/d\eta^{\text{jet}}$  for jets in events (dots) containing at least one  $D^*$  meson for different regions in  $E_T^{\text{jet}}$ . The comparison is made to massive QCD predictions with (solid line) and without (dotted line) hadronisation corrections applied. The theoretical uncertainties (hatched band) come from the change in scales simultaneously with the change in charm mass. The beauty component is also shown (lower histogram).



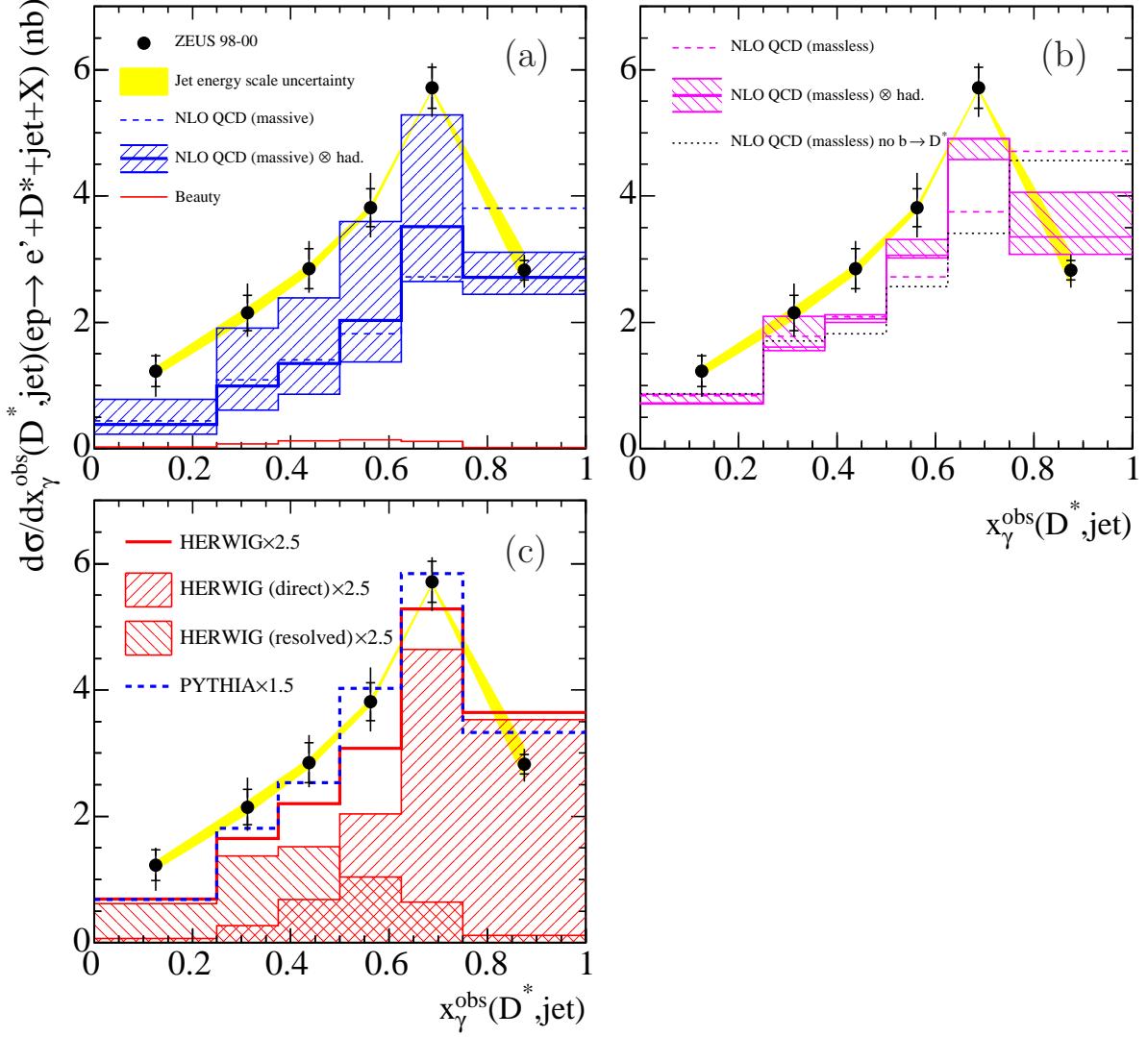
**Figure 6:** Cross-section  $d\sigma/d\eta^{\text{jet}}$  for  $D^*$ -tagged jets and untagged jets (dots). The comparison is made to massive QCD predictions with (solid line) and without (dashed line) hadronisation corrections applied. The beauty component is also shown (lower histogram). For the untagged jet distribution, the massless QCD predictions are also shown with (solid line) and without (dashed line) hadronisation corrections applied. The theoretical uncertainties (hatched bands) come, in the case of the massive calculations, from changing renormalisation and factorisation scales as well as the charm mass simultaneously. In the case of the massless calculations, they come from changing the scales only. The prediction with no component from  $b$ -quark fragmentation to a  $D^*$  is also shown (dotted line).

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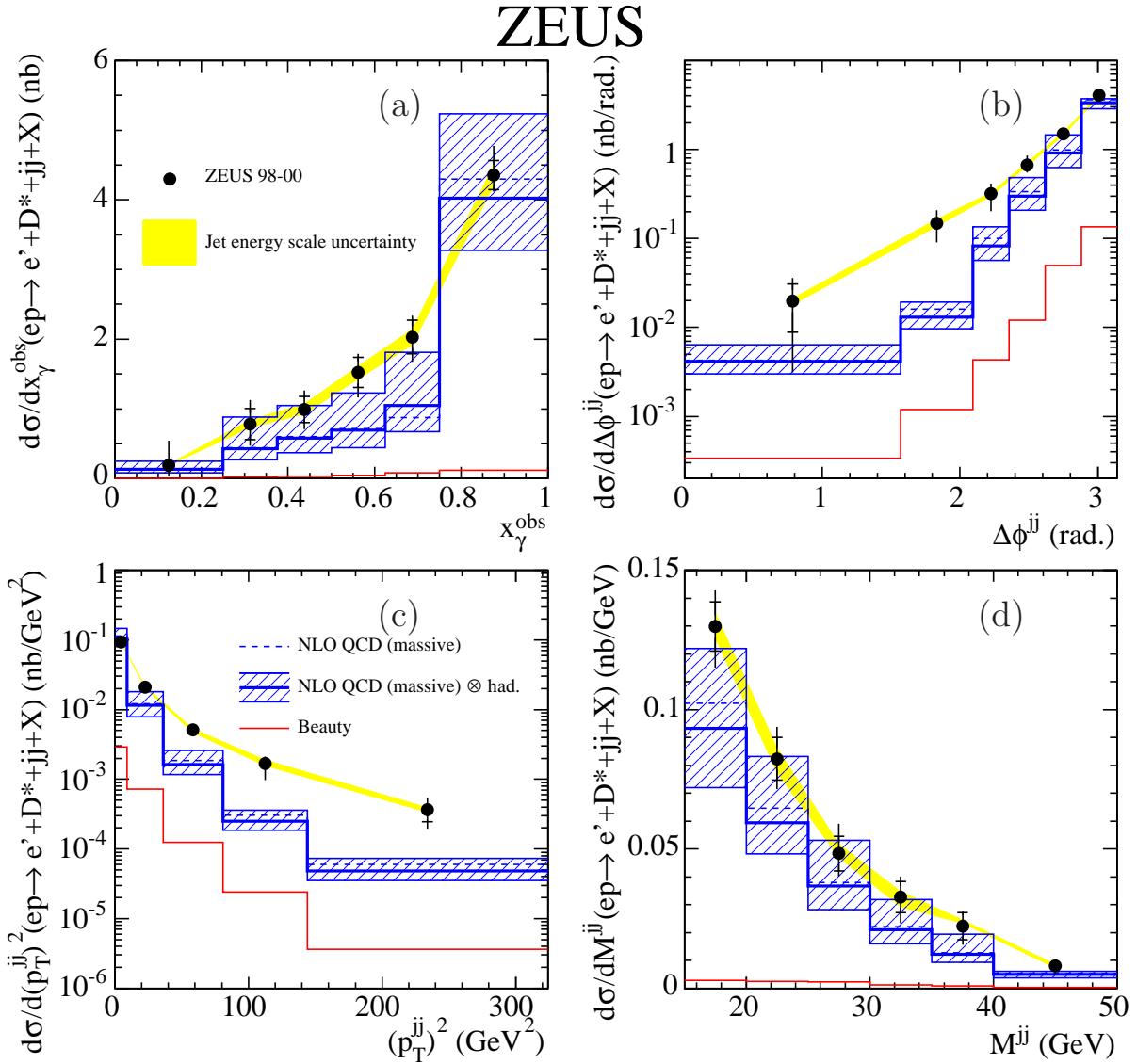


**Figure 7:** Cross-sections  $d\sigma/dE_T^{\text{jet}}$  and  $d\sigma/d\eta^{\text{jet}}$  in bins of  $p_T^{D^*}$ . The data (solid dots) are compared to the massive QCD predictions with (solid line) and without (dotted line) hadronisation corrections applied. The theoretical uncertainties (hatched band) come from the change in scales simultaneously with the change in charm mass. The beauty component is also shown (lower histogram).

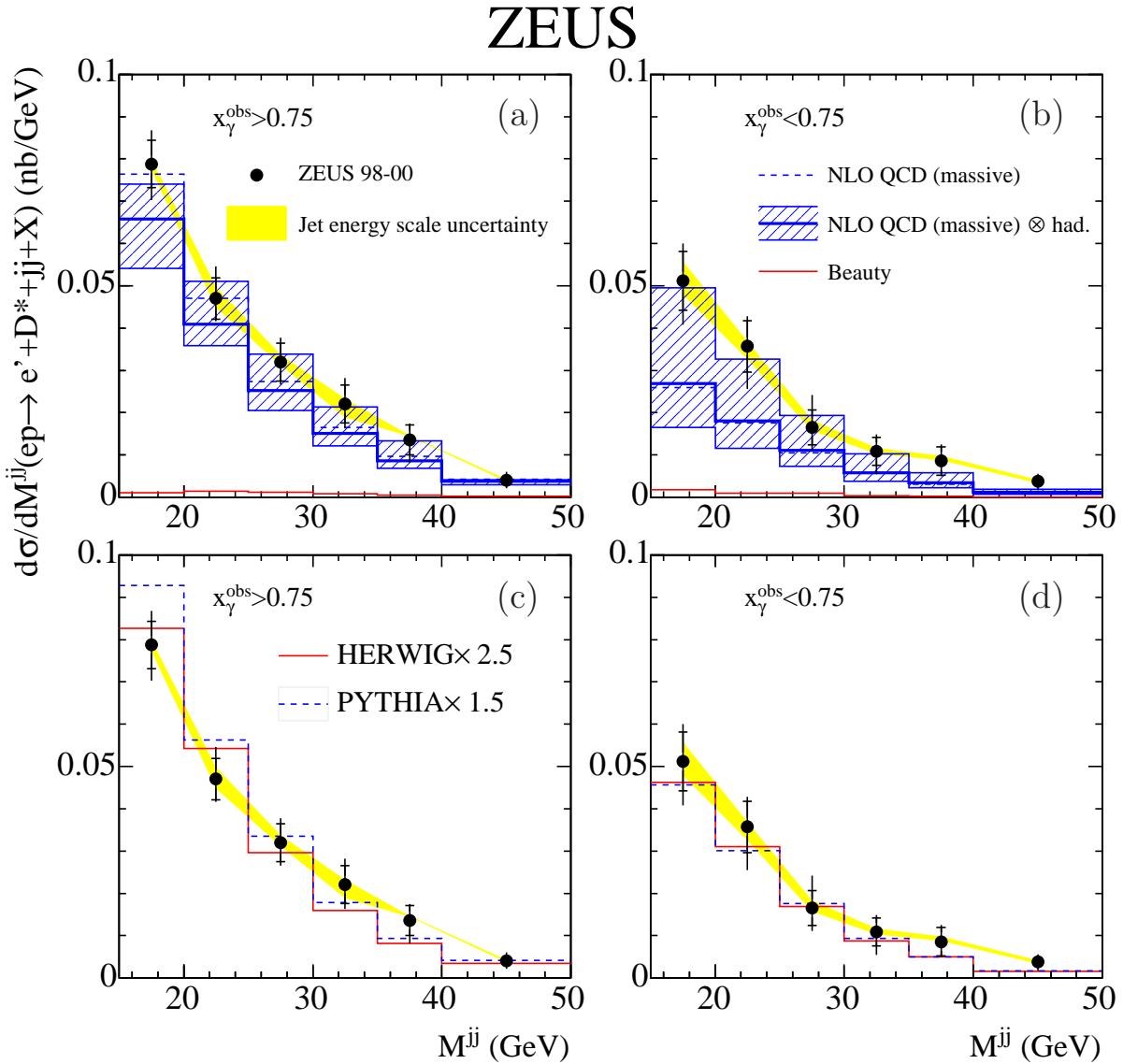
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**Figure 8:** Cross-section  $d\sigma/dx_\gamma^{\text{obs}}(D^*,\text{jet})$  for the events containing a  $D^*$  meson not associated with a jet. The data (solid dots) are compared to (a) the massive QCD predictions with (solid line) and without (dotted line) hadronisation corrections applied. The beauty component is also shown (lower histogram). In (b) the data are compared to the massless QCD predictions shown with (solid line) and without (dotted line) hadronisation corrections applied. The prediction with no component from  $b$ -quark fragmentation to a  $D^*$  is also shown (dotted line). The theoretical uncertainties (hatched bands) come, in the case of the massive calculations, from changing renormalisation and factorisation scales as well as the charm mass simultaneously. In the case of the massless calculations, they come from changing the scales only. In (c) the data are compared to HERWIG (solid line) and PYTHIA (dashed line) MC predictions normalised to the data. The predicted HERWIG direct and resolved contributions are also shown.

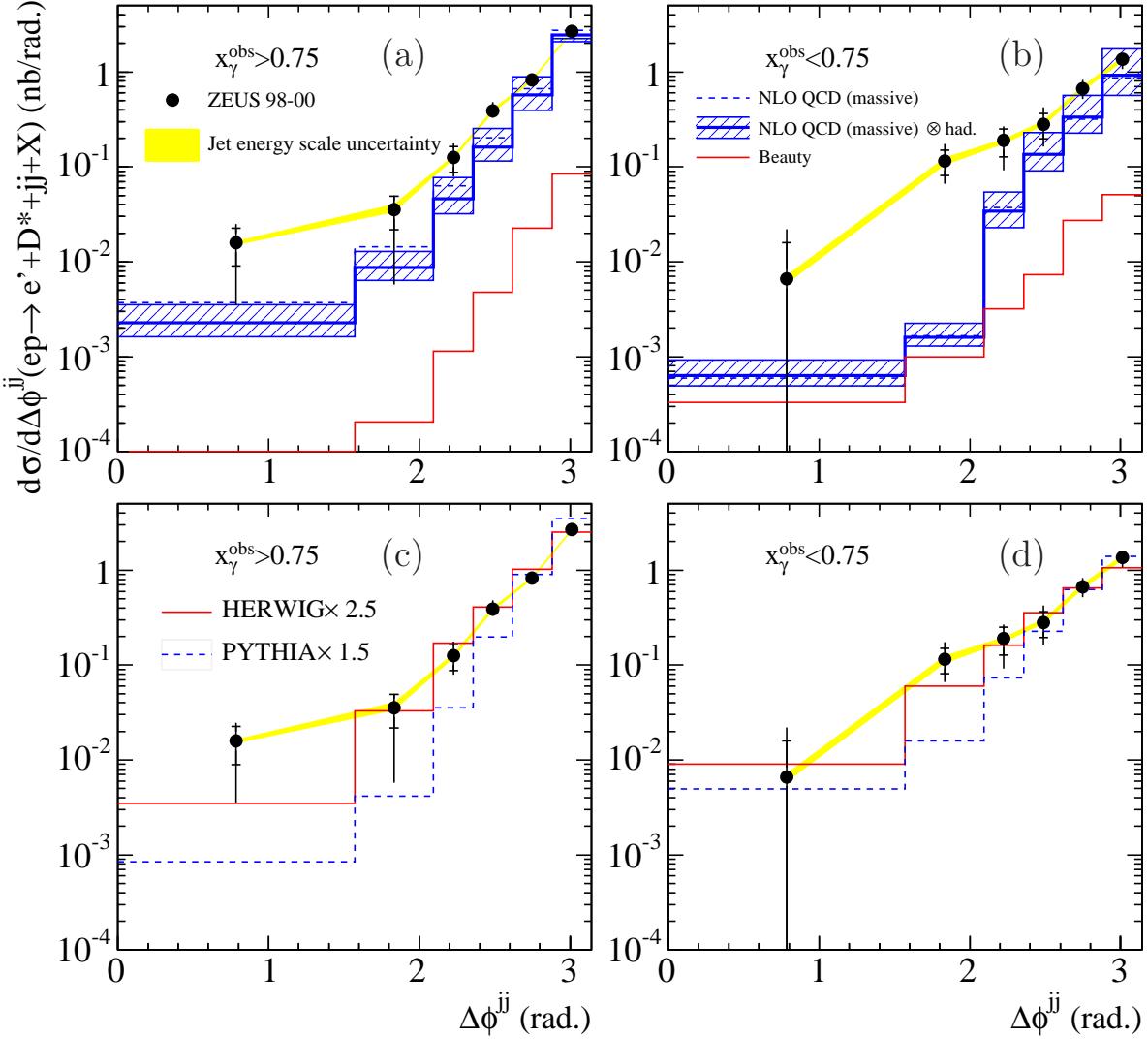


**Figure 9:** Dijet cross-sections (a)  $d\sigma/dx_\gamma^{\text{obs}}$ , (b)  $d\sigma/d\Delta\phi^{jj}$ , (c)  $d\sigma/d(p_T^{jj})^2$  and (d)  $d\sigma/dM^{jj}$  for the data (solid dots) compared to massive QCD predictions with (solid line) and without (dotted line) hadronisation corrections applied. The theoretical uncertainties (hatched band) come from the change in scales simultaneously with the change in charm mass. The beauty component is also shown (lower histogram).



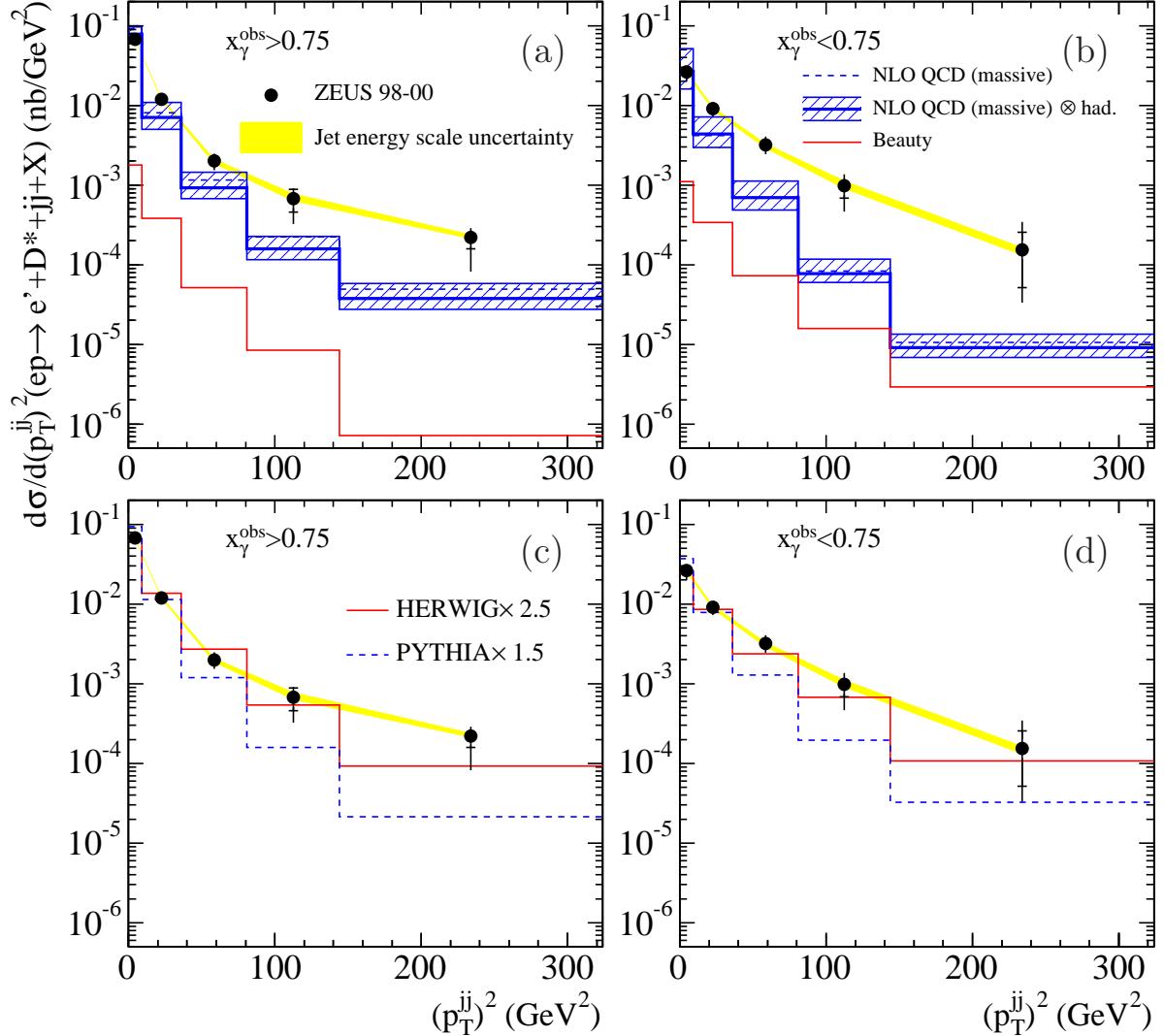
**Figure 10:** Cross-section  $d\sigma/dM^{jj}$  separated into (a,c) direct enriched ( $x_{\gamma}^{\text{obs}} > 0.75$ ) and (b,d) resolved enriched ( $x_{\gamma}^{\text{obs}} < 0.75$ ). The data (solid dots) are compared (a,b) to the massive QCD prediction with (solid line) and without (dotted line) hadronisation corrections applied. The theoretical uncertainties (hatched band) come from the change in scales simultaneously with the change in charm mass. The beauty component is also shown (lower histogram). The data are also compared (c,d) with HERWIG (solid line) and PYTHIA (dashed line) MC predictions multiplied by the indicated factors.

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**Figure 11:** Cross-section  $d\sigma/d\Delta\phi^{jj}$  separated into (a,c) direct enriched ( $x_\gamma^{\text{obs}} > 0.75$ ) and (b,d) resolved enriched ( $x_\gamma^{\text{obs}} < 0.75$ ). The data (solid dots) are compared (a,b) to the massive QCD prediction with (solid line) and without (dotted line) hadronisation corrections applied. The theoretical uncertainties (hatched band) come from the change in scales simultaneously with the change in charm mass. The beauty component is also shown (lower histogram). The data are also compared (c,d) with HERWIG (solid line) and PYTHIA (dashed line) MC predictions multiplied by the indicated factors.

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**Figure 12:** Cross-section  $d\sigma/d(p_T^{jj})^2$  separated into (a,c) direct enriched ( $x_\gamma^{\text{obs}} > 0.75$ ) and (b,d) resolved enriched ( $x_\gamma^{\text{obs}} < 0.75$ ). The data (solid dots) are compared (a,b) to the massive QCD prediction with (solid line) and without (dotted line) hadronisation corrections applied. The theoretical uncertainties (hatched band) come from the change in scales simultaneously with the change in charm mass. The beauty component is also shown (lower histogram). The data are also compared (c,d) with HERWIG (solid line) and PYTHIA (dashed line) MC predictions multiplied by the indicated factors.